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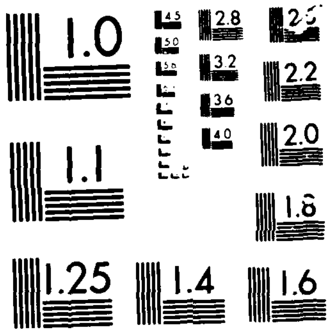
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Monterey, California

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DURING AIRCRAFT CONCEPTUAL DESIGN

by

Robert John Gilman

March 1986

Thesis Advisor: R.E. Ball

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Survivability Considerations during Aircraft Conceptual Design

by

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Lieutenant, United States Navy
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Submitted in partial fulfillment of the requirements for the degree of

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ABSTRACT

Survivability, capability, maintainability, and reliability will establish the effectiveness of a combat aircraft. Considerations for the "ilities" must take place during the conceptual design phase. Retrofit of survivability enhancement has historically increased weight, drag, and cost, while decreasing capability and performance. Proper application of the six susceptibility reduction concepts and the six vulnerability reduction concepts must take place before the design is established to maximize effectiveness and minimize penalties. In this thesis, the application of survivability enhancement techniques to the conceptual design is presented in general and also specifically applied to the design of a long range Strike Fighter aircraft. General guidelines for susceptibility and vulnerability reduction for any aircraft are also presented.

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I. INTRODUCTION

Incorporation of survivability in the initial design process cf an aircraft is a concept that must be used from the first conceptual sketch a designer produces. Given a mission, which will include a payload, mission profile, and other mission specifications, the designer can now begin the design process, attempting to create the most effective weapon system possible that meets all of the specifications. Once the aircraft design is established, it may be too late to incorporate survivability features that will make an aircraft ready for actual combat. Post design survivability enhancement fixes have historically added weight, drag, and cost, while decreasing range or payload, speed, and other performance parameters. This thesis considers the need for survivability enhancement during the conceptual design process rather than depending upon retrofit of the aircraft to make it a survivable weapon system. Survivability considerations during the conceptual design for a long range strike fighter will be reviewed. Survivability must be designed into an aircraft, just as leading edge sweep angle is set for a design mach number.

A. AIRCRAFT SURVIVABILITY

How is an aircraft made to be a survivable combat weapon system? This question is not easily answered because

of the complexity of the aircraft design process and the interaction of the aircraft's physical parameters. Previously, many rules of thumb have surfaced as design guidelines to a survivable aircraft. These design rules have come from combat experience as lessons learned. During non-combat years, the military and defense aircraft industry tend to drift away from combat lessons learned due to cost and weight constraints. An aircraft without any survivability enhancement features may have a lower price tag and also better flight performance than a similar aircraft with survivability built into it. On the surface, it may appear that the cheaper aircraft is a better buy. However, in combat conditions, the aircraft with the survivability features may be in fact a better aircraft.

The term effective is used a great deal by the aircraft industry when discussing new designs. Combat attack aircraft must be effective. They must be able to reach, locate, and then destroy their target. However, being an effective aircraft and a survivable aircraft are interdependent goals. An aircraft that is shot down prior to the target is not an effective weapon system at all. Also, an aircraft must be able to safely return from its mission to complete its goal of effectiveness. Figure 1-1 is an illustration from Thronson [Ref. 1] and shows the effect of different attrition rates upon the total force. It is evident that 3% loss rate is unacceptable for a

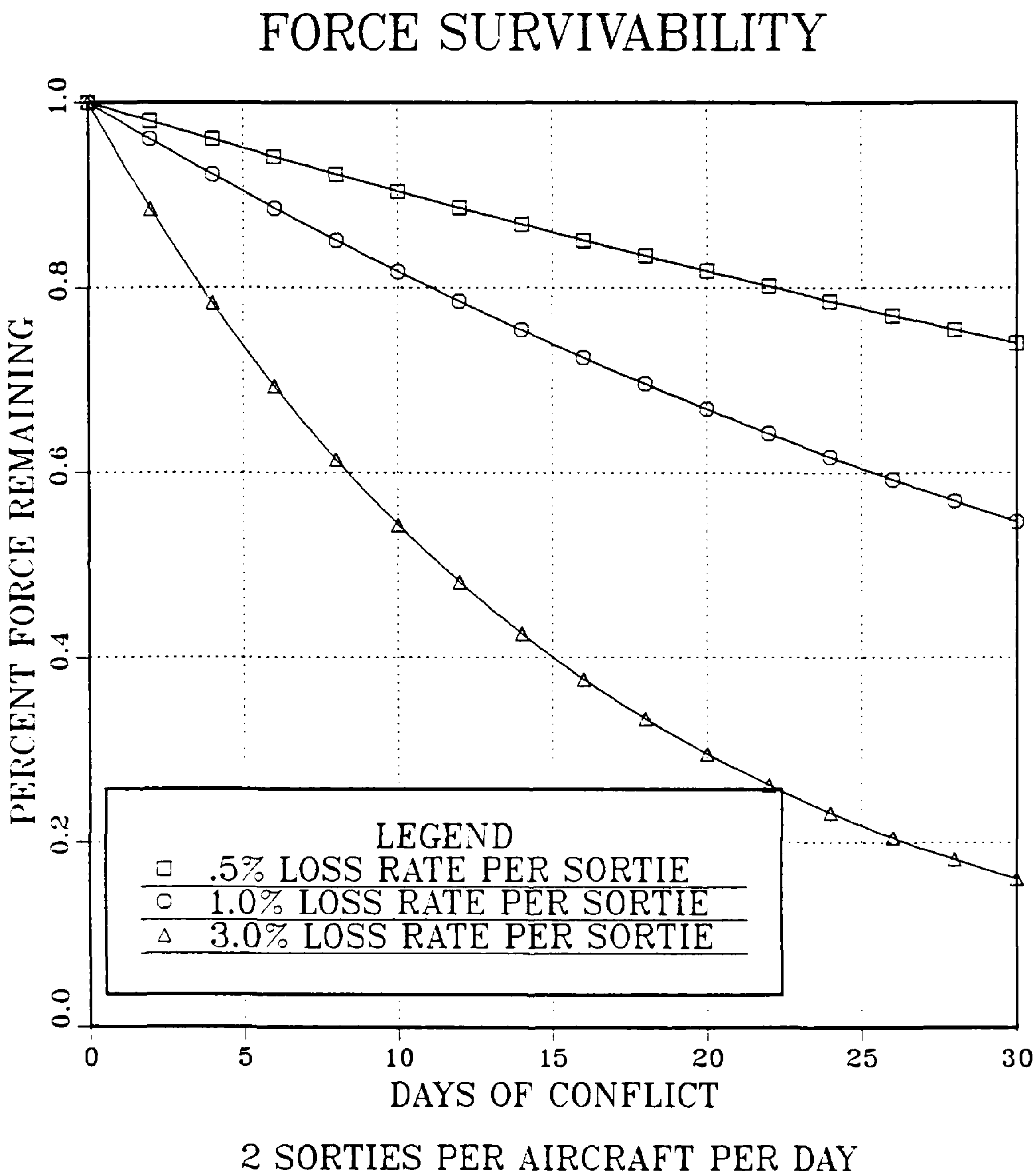


Figure 1-1 Force Survivability

conflict of any duration. Survivability enhancement must be a consideration during all phases of aircraft design. Aircraft that are not survivable do not last long as shown in Figure 1-1.

If an aircraft has survivability features that will allow it to fly with damage that would otherwise ground or kill another aircraft, it is a more effective weapon system. One example is self-sealing fuel tanks that are more expensive than wet bladder tanks. These two types of tanks perform exactly the same until they are hit by an enemy projectile. The cost of the self-sealing tank may be suddenly justified in terms of survivability.

B. GOALS FOR SURVIVABILITY DESIGN

The goals in making a combat aircraft survivable are listed in Table I-1.

TABLE I-1

SURVIVABILITY GOALS

(1) Delay detection as long as possible

(2) If detected, avoid being fired at

(3) If fired at, avoid being hit

(4) If hit, avoid weapon system kill

(5) If hit, avoid aircraft kill

(6) If hit and not killed, can be easily repaired

Some of the ways to achieve the above goals may seem to have nothing to do with aircraft design. For example, the tactics of an attacking aircraft may be a large factor in delaying detection. However, the tactics of an attacking aircraft are built around the aircraft capabilities. Tactics employ the pilot and aircraft to accomplish their best in any given situation. Therefore, survivability is intertwined with the aircraft design.

C. SURVIVABILITY DEFINITIONS

The following five definitions will be used throughout this thesis and are taken from Ball [Ref. 2].

(1) Aircraft Survivability; The capability of an aircraft to avoid and or withstand a man-made hostile environment.

(2) Vulnerability; The inability of an aircraft to withstand the damage caused by the hostile ervironment.

(3) Susceptibility; The inability of an aircraft to avoid (being damaged by) the hostile environment.

(4) Damage Mechanism; The output of the warhead that causes damage to the target. It is the phsyical description of the tangible instrument or measurable quantity designed to inflict damage upon the target.

(5) Survivability Enhancement; Any particular characteristic of the aircraft, specific piece of equipment, design technique, armament, or tactic that reduces either the susceptibility of the vulnerability of the aircraft has the potential for increasing the survivability of the aircraft.

Susceptibility restated is the inability of the aircraft to avoid being hit by an enemy threat mechanism. Vulnerability restated is the inability of the aircraft to

withstand stand that hit. Both susceptibility and vulnerability are terms that denote poor traits in an aircraft. Thus, we want to reduce both susceptibility and vulnerability in any aircraft. Susceptibility reduction refers to survivability goals 1 through 3 and vulnerability reduction refers to goals 4 through 6.

Susceptibility = P_h (Probability of hit)

Vulnerability = $P_{k/h}$ (Probability of kill given a hit)

Probability of kill = $P_k = P_h P_{k/h}$

Survivability = $P_s = 1 - P_k$

Thus, to increase aircraft survivability we need to decrease susceptibility and also decrease vulnerability. Any conflicts between decreasing vulnerability with a consequential increase of susceptability must be evaluated to determine the correct mix to maximize survivability. Tables I-2 and I-3 list the six susceptibility and the six vulnerability reduction concepts.

TABLE I-2

SUSCEPTIBILITY REDUCTION CONCEPTS

(1) Threat Warning

(2) Noise Jammers and Deceivers

(3) Signature Reduction

(4) Expendables

(5) Threat Suppression

(6) Tactics

TABLE I-3

VULNERABILITY REDUCTION CONCEPTS

(1) Component Redundancy with Separation

(2) Component Location

(3) Passive Damage Suppression

(4) Active Damage Suppression

(5) Component Shielding

(6) Component Elimination

II. SUSCEPTIBILITY REDUCTION CONCEPTS

A. GENERAL

If an aircraft could be designed to have zero susceptibility in all circumstances, the aircraft would be a completely survivable combat weapon system. The concept of zero susceptibility relates to goals 1 through 3. In reality, no aircraft can be designed and used with zero susceptibility. Therefore, it is the designer's goal to reduce the susceptibility of the conceptual aircraft design to a "satisfactory" level.

B. ELECTRONIC METHODS AND EXPENDABLES

The first three susceptibility reduction concepts of Table I-1, which are:

(1) Threat Warning

(2) Noise Jammers and Deceivers

(3) Expendables

may appear to have a very small influence upon aircraft conceptual design. However, we must realize that the radar warning receiver, electronic countermeasures (ECM) equipment, and weapons payload are part of the aircraft's total payload. The aircraft's total payload may be used to obatin the initial weight approximation for further conceptual design calculations. For any aircraft during conceptual design, a combination of payload weight must be selected.

Figures 2-1, 2-2, and 2-3 are illustrations from Schlessinger [Ref. 3], where different combinations of countermeasures equipment and bombs are examined for a given size attack aircraft. The maximum payload of countermeasures equipment and bombs for this aircraft is first established at 10,000 lbs to calculate the approximate size of the conceptual design. Figure 2-1 illustrates the increase in P_s with an increase of countermeasures weight and a corresponding decrease in bombs for a typical surface to air missile (SAM) encounter. The figure shows that more countermeausres equipment is better up to a point where the probability of survival begins to level off. The probability of survival is established considering all of the aircraft's survivability enhancement features and the threat. Figure 2-2 shows the mission attainment measure (MAM) for the same attack aircraft of Figure 2-1. The MAM ranges from 0 to 100% target destruction in the presence of the enemy threat, but without threat effects to degrade the MAM. The slope of the MAM curve is continuously decreasing as higher weapons loads and smaller countermeasures loads are carried. To obtainthe most effective combination of countermeasures equipment and bombs, the measure of mission success (MOMS) is calculated.

$$MOMS = P_s * MAM \tag{2.1}$$

Figure 2-3 shows MOMS vs. pounds of countermeasures equipment/pounds of bombs. For this example the peak MOMS

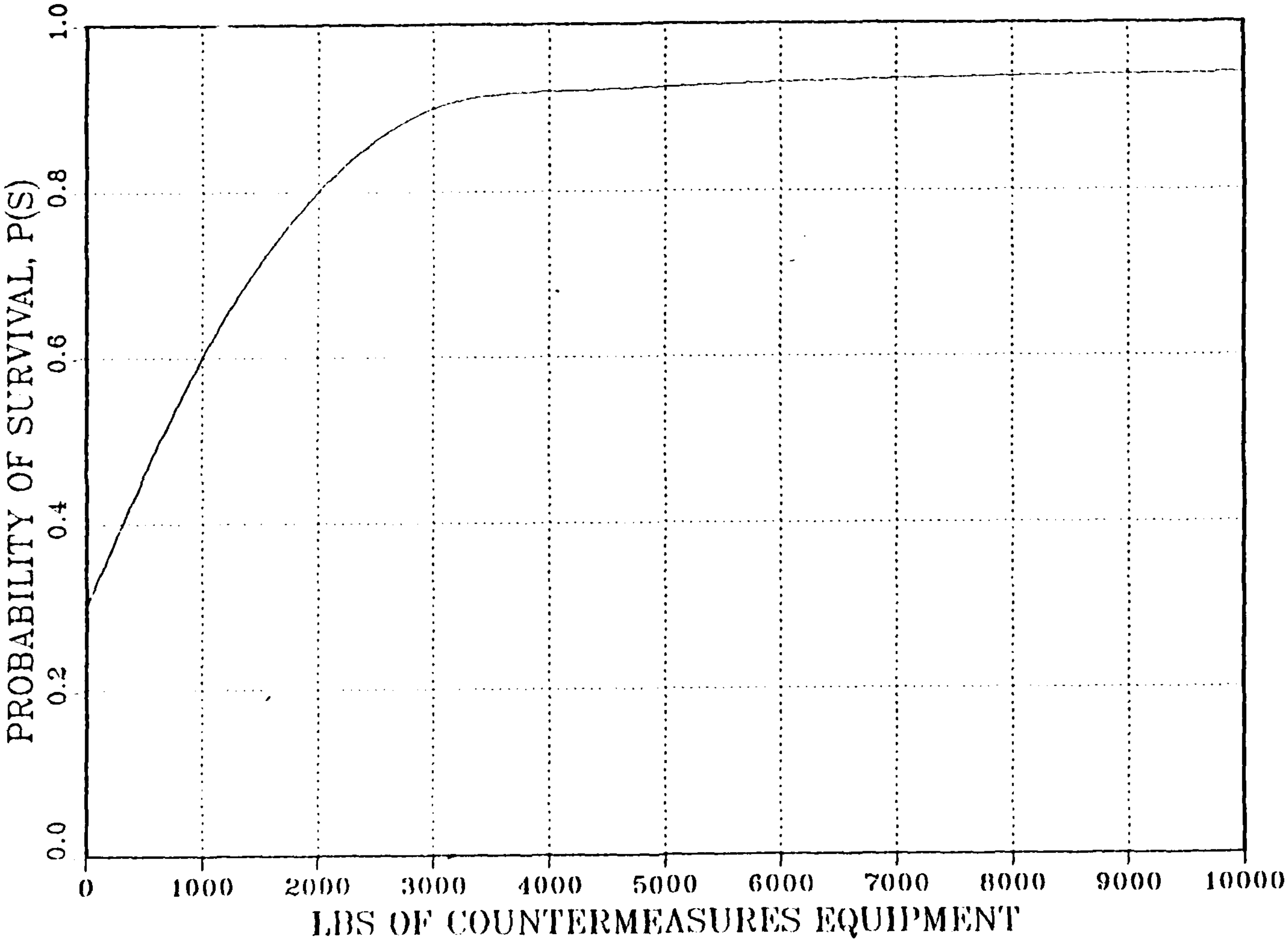


Figure 2-1 Probability of Survival vs. Countermeasures

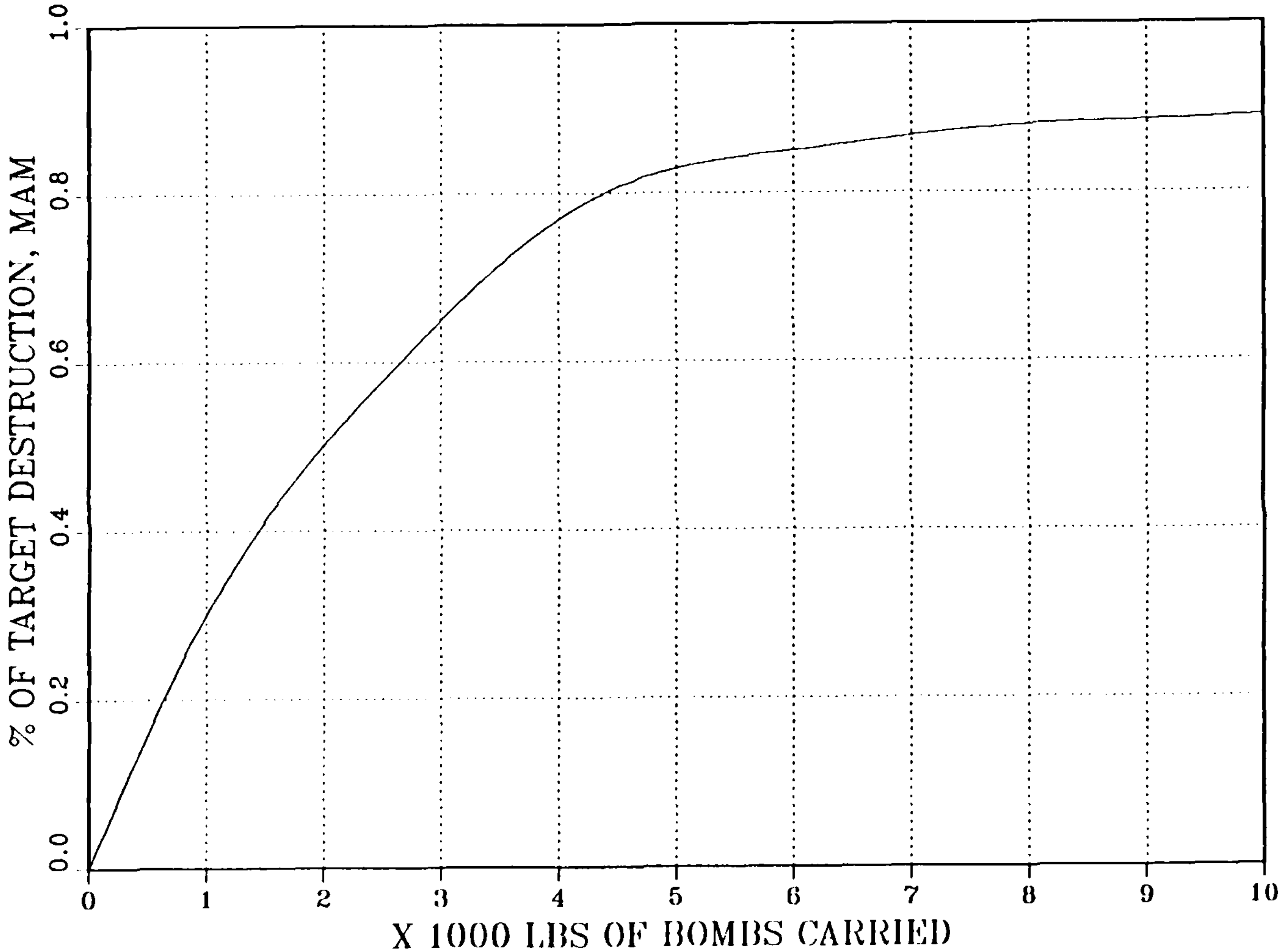


Figure 2-2 Mission Attainment Measure

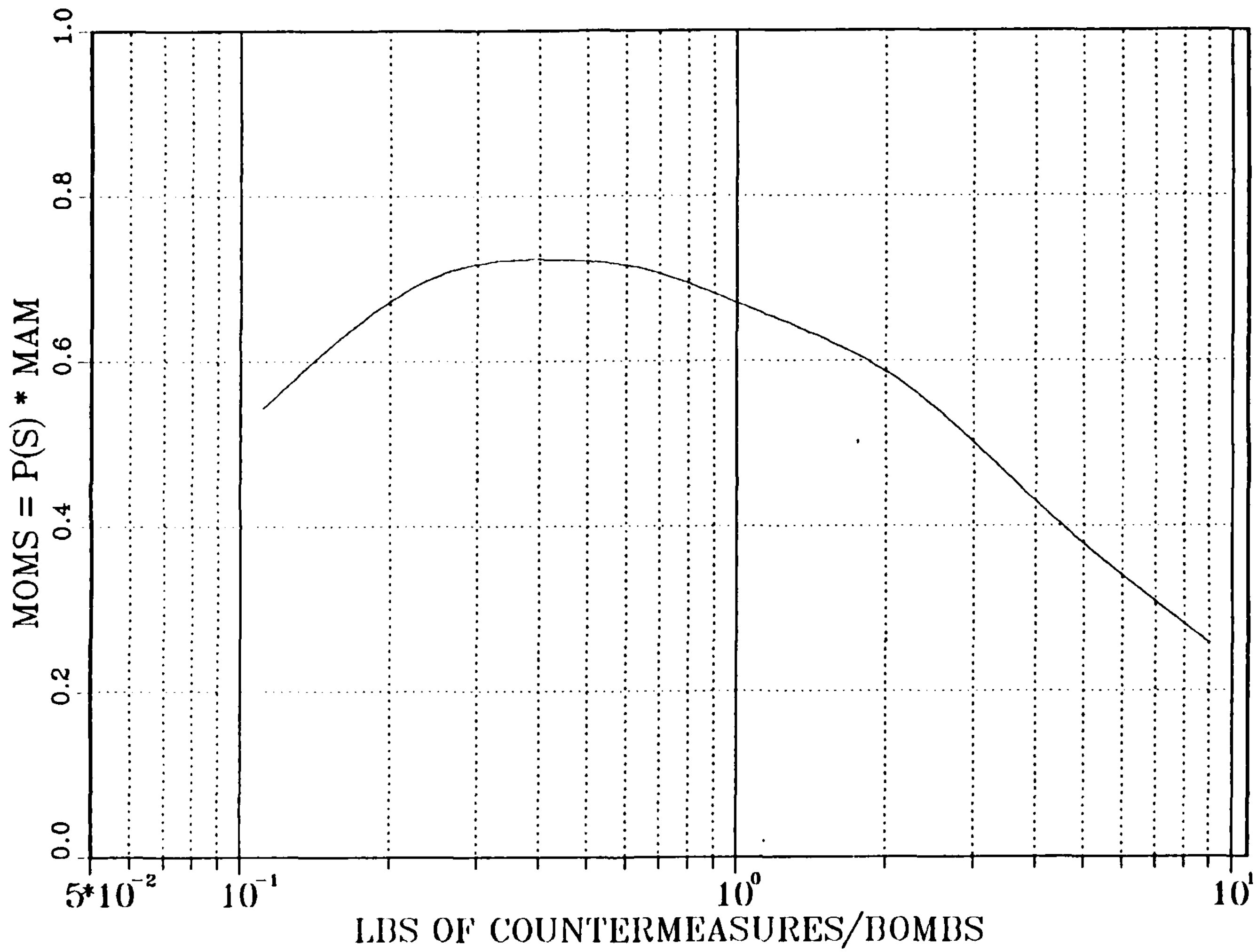


Figure 2-3 Measure of Mission Success

occurs at a countermeasure/bomb ratio of approximately 0.4. This is equivalent to 2,900 lbs of countermeasure equipment and 7,100 lbs of bombs for the total payload of 10,000 lbs.

If the conceptual design aircraft's total payload remains constant, these three figures will aid in maximizing the MOMS. However, if the aircraft's payload is allowed to increase with more countermeasures equipment, or more bombs, the design aircraft's weight, size, and P_s will change. The payload weight is a very sensitive parameter for conceptual design weight calculations. For example, an increase in aircraft payload may mean up to a factor of 3 times that increase in actual aircraft weight. For a new aircraft design, which is heavier and certainly larger, a new P_s must be calculated and used to pick the most effective countermeasures load and weapons load combination.

C. THREAT SUPPRESSION

Threat suppression is the fourth method listed for susceptibility reduction. This is a very active means of increasing survivability. Any type of action that causes the enemy to reduce the amount of anti-aircraft threat, will most likely increase survivability. Self-protection missiles and anti-radiation missiles (ARM) are examples of threat suppression. They can significantly affect the survivability and success of a strike. The ability to carry and effectively use threat suppression weapons should be considered in any new aircraft design.

D. SIGNATURE REDUCTION

A military aircraft has many different types of signatures or observables. These signatures are:

(1) Visual

(2) Radar

(3) Infrared

(4) Aural

(5) Electromagnetic Emissions

These signatures are important parameters when the combat aircraft is in the conceptual design stage. The reduction of all of the above signatures are extremely important because the enemy will use these signatures to detect, guide, and possibly fuse antiaircraft weapons.

1. Visual Signature Reduction

The four parameters that affect the visual signature of an aircraft are luminance, chromaticity, clutter, and movement. Luminance is the most important parameter effecting the visual signature. The difference between the background luminance and the aircraft luminance is the parameter of interest. Special paint and aircraft lighting can reduce the visual signature of an aircraft by reducing the contrast of luminance. For the aircraft design team, the major impact of visual signature is physical size. The smaller the aircraft the less effect luminance contrast will have. Because many anti-aircraft weapons are visually directed, a smaller aircraft may have a better

chance for survival and also be more effective because it is harder to see.

Aircraft engine exhaust smoke is also a major contributor to the visual signature. However, modern combustion techniques may have solved the exhaust smoke problem of turbojet and turbofan engines.

2. <u>Infrared Signature Reduction</u>

The parameters for the designer that affect the infrared signature are engine temperatures, the exhaust plume, aircraft surface emissivity and reflectivity, and other heat producing aircraft components. If aircraft hot parts can be cooled or masked, any infrared (IR) countermeasures used will be much more effective.

The use of turbofan engines reduces the temperature of the exhaust gases due to the mixing of cool bypass air. The afterburner of a turbofan however, is much hotter than the afterburner of a turbojet because more fuel must be fed to the afterburner section to completely burn the extra bypass air.

The exhaust plume IR radiation may be reduced by mixing cooler air with the exhaust just before or immediately after the exit nozzle. A nozzle that can cool the exhaust plume quickly, is a two-dimensional nozzle. The circular turbine exit duct is transitioned to a rectangular exhaust nozzle. The two-dimensional nozzle vortices from the nozzle corners, induce quick mixing of the exhaust and

ambient air. More nozzle perimeter may also help reduce the IR signature.

3. Radar Signature Reduction

The conceptual design is the most important starting point for the reduction of the aircraft's radar signature. Aircraft radar cross section (RCS), in square meters, is the measure of radar signature. Just about every conceptual design parameter will have an effect upon the RCS of the aircraft. The radar range equation from Ball [Ref. 2]:

$$R = [(P_t G_t \sigma A_e)/(4\pi)^2 S_{min}]^{1/4} \qquad (2.2)$$

shows that if σ, the RCS of the aircraft is reduced by 50%, the detection range R is reduced by 16%. A benefit of RCS reduction that has a earlier payoff is the on-board ECM equipment becomes much more effective. The on-board jammer operates one way (between aircraft and radar) so the burn through range (where the target RCS can be seen through the jamming) varies as the 1/2 power with σ. From Ball [Ref. 2], the radar equation in the presence of jamming is:

$$R = [(P_r G_r \sigma C)/(P_j B G_j 4\pi)]^{1/2} \qquad (2.3)$$

This equation shows that a 50% reduction in σ (RCS), will reduce the burn through or detection range by 30%. The

above examples of 50% reduction of RCS may seem like a large amount, but actual RCS reductions of 80% to 90% may be possible.

Figure 2-4 is taken from Ball [Ref. 2], and illustrates equations (2.2) and (2.3). The figure shows that the benefit of RCS reduction, is reduced detection range. Another benefit of RCS reduction, is the on board jammer power required to maintain a constant jam to signal (J/S) ratio also decreases with RCS reduction. Reduced jammer power required will mean a smaller and lighter jammer, which are both beneficial results to the design.

From Ball [Ref. 2], there are three methods to reduce the RCS of an aircraft.

(1) reflection of the radar signal away from any receiving antenna

(2) absorption of the radar signal by attenuation or interference

(3) active interference with surface currents

Methods 1 and 2 will directly affect the conceptual design process. Method 3 is an electronic or material method which may mean an increase of electronic weight.

Most aircraft construction materials act as reflectors to a radar signal. RCS reduction method 1 attempts to reduce the radar reflected toward the receiver as much as possible. This is done by designing the aircraft with curved smooth surfaces and reducing the number of sharp protrusions and indentations or cavities. Locations

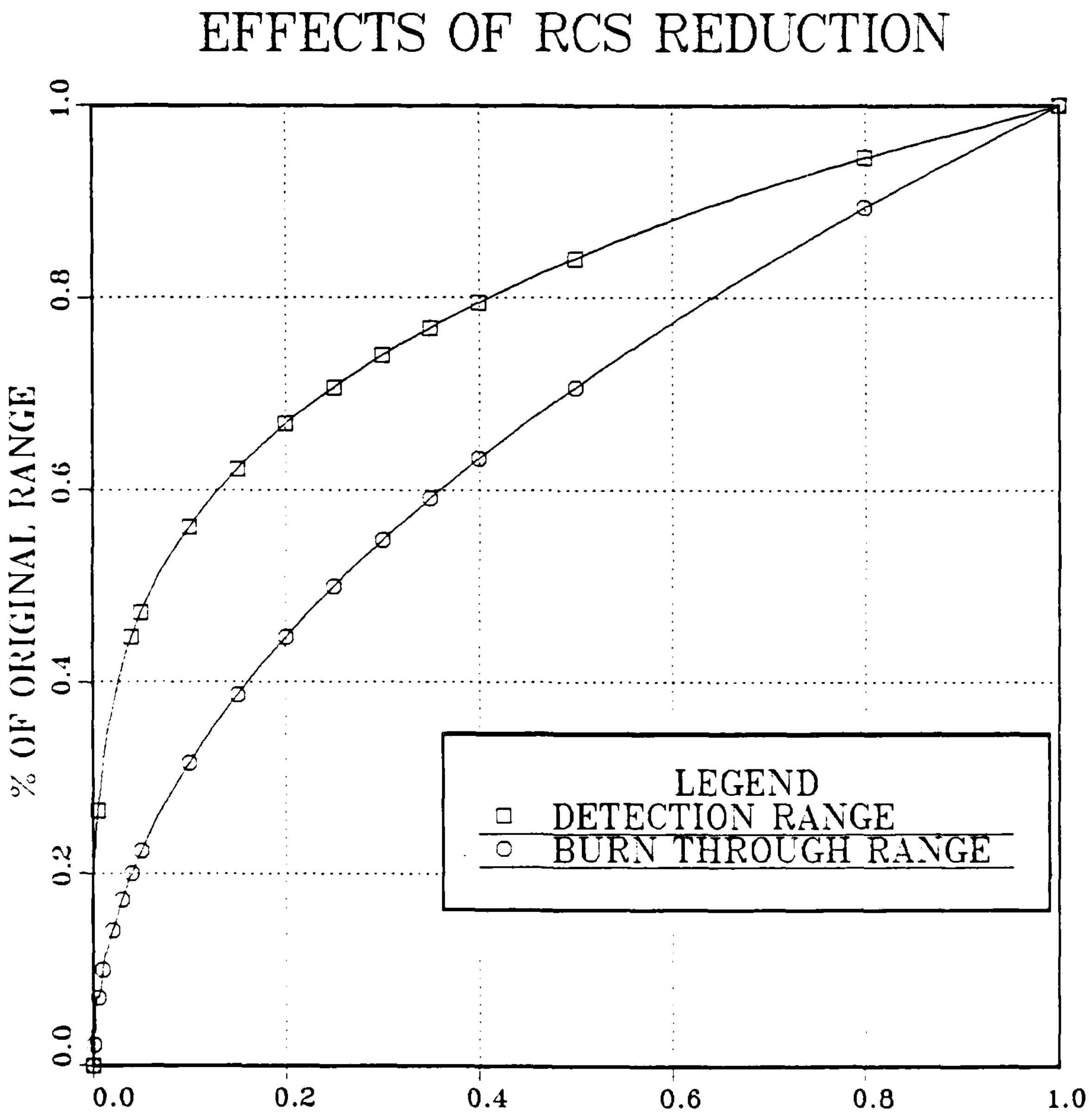


Figure 2-4 Effects of RCS Reduction

on the aircraft where a radar signal can reradiate off multiple aircraft surfaces, are more likely to reflect the signal in the direction of the radar receiver. Also, for materials that are radar transparent, care must be taken to prevent radar backscatter from behind the transparent exterior. Present construction materials used to make radomes and canopies are examples of materials that allow the radar signal to pass through. Structural composites may also be transparent to a radar signal. However, if a radar reflective material is under the composite, the resulting aircraft RCS may be much higher than expected. Major contributors to aircraft RCS are:

(1) engine intakes
(2) external weapons stations/racks
(3) external weapons
(4) pod mounted engines
(5) radar compartment
(6) cockpit
(7) wing/fuselage interface
(8) exterior lights compartments
(9) external mounted antennas
(10) leading edges of the wing and stabilizers

Radar absorbent material (RAM) can be used in vehicle areas where reflection of the electromagnetic energy away from the radar receiver is difficult. However, the RAM may be very heavy material, and its radar absorbent

qualities may be frequency dependent. RAM can be used by the design team in those local areas of high RCS where reflection away from the radar receiver is impractical due to costs or conflicting design goals.

4. Aural Signature Reduction

The aural signature of an aircraft may be a factor in the aircraft's survivability during combat. With reduction of the aural signature, detection of the aircraft may be delayed. Antisubmarine aircraft may be more concerned with aural signature than fighter or strike aircraft due to the battle field they probably will operate in. Propulsion systems contribute most of the aural signature, and different methods can be used to reduce the level of noise. Current civilian aircraft use noise reduction designs to reduce noise around airports. Trade-off studies will indicate the benefit of noise reduction designs verses performance and cost.

5. Electromagnetic Signature Reduction

The electromagnetic emissions from a military aircraft must be considered when designing for low aircraft signatures. While intentional electromagnetic emissions may aide the aircrew in accomplishing their mission, the enemy may use the aircraft's electromagnetic emissions to detect and fire upon the aircraft, particularly if the other signatures have been significantly reduced. Communication, navigation, and weapons delivery equipment that are

passive, or are of very short duration, reduce the active emissions from the aircraft.

E. TACTICS

Susceptibility reduction by the use of tactics is a very important method of increasing survivability. Tactics for combat aircraft vary greatly depending upon the aircraft, mission, threat, weapons, and many other influencing conditions. The use of proper tactics will give the combat aircrew the best chance to complete their mission and safely return. The tactics are essentially built around the aircraft's capabilities and the mission it is to fulfill.

When the military sends a request for proposal (RFP) to industry, the tactics that the future aircraft will use have had a direct impact upon the specifications contained in the RFP. In a sense, the threat that the aircraft will meet drives the tactics, and the tactics drive the RFP (specifications). The aircraft company now must design an aircraft that will meet as many of the specifications possible and be more "attractive" than the competition. Table II-1 contains many conceptual design parameters that will influence the tactics of the aircraft.

TABLE II-1

CONCEPTUAL DESIGN PARAMETERS THAT INFLUENCE TACTICS

(1) Mission Profile

(2) Max Speed (Sea Level and Altitude)

(3) Turning Performance

(4) Load Factors

(5) Range

(6) Endurance

(7) Take Off Distance

(8) Landing Distance

(9) Signatures

(10) Weapons Payload (Type and Number)

(11) Avionics and Countermeasures Equipment

(12) Instrumentation (Radar, Cockpit Displays)

(13) Special Capabilities (In Flight Refueling, Carrier Launch/Arrest, etc.)

III. VULNERABILITY REDUCTION CONCEPTS

A. GENERAL

The reduction of aircraft vulnerability takes into consideration that the aircraft has already been hit by one or more damage mechanisms. Survivability goals four through six of Table I-1 are associated with aircraft vulnerability reduction. Table I-3 lists the six vulnerability reduction concepts that will be discussed in this chapter. The conceptual design team should always take into consideration the vulnerability of the design of the aircraft and strive to reduce it.

To determine the vulnerability of an aircraft, the possible causes of an aircraft kill must be identified. The damage or loss of any component that leads to an aircraft kill is identified as a critical component. Table III-1 lists five possible critical components. Each of the critical components is evaluated to determine the probability of component kill ($P_{k/h}$), given a hit on the component. The $P_{k/h}$ for each component is calculated due to impact of a fragment or penetrator. The determination of $P_{k/h}$ is difficult to accurately determine. Testing of the component to determine the component probability of kill will aide the analysis, however, incendiary effects, fragment breakup, and spall must also be considered. The

more protected a component, the lower the $P_{k/h}$ may become due to reduced or zero velocity of impact.

TABLE III-1

POSSIBLE CRITICAL COMPONENTS

(1) Pilot

(2) Propulsion System

(3) Fuel System

(4) Flight Control System

(5) Major Structural Members

The area of the component presented to the damage mechanism is multiplied by the component $P_{k/h}$ to obtain the component vulnerable area (A_v). Each component vulnerable area will change with different aspect to the damage mechanism shotline. Components that are redundant or provide a backup function, (e.g., two engines) are called redundant critical components if the loss of more than one of these components leads to the loss of the aircraft. The aircraft vulnerable area (A_V), is the combination of the individual nonredundant and redundant critical component vulnerable areas. The vulnerability reduction concepts of Table I-3 will reduce the vulnerable area of the critical components and the vulnerable area of the aircraft. The goal of a "small" vulnerable area should be strived for by the design team.

B. COMPONENT REDUNDANCY WITH SEPARATION

The entire aircraft, from the major aircraft systems to the weapons the aircraft will carry, must be evaluated to determine the nonredundant and redundant critical components. Once these critical components are identified, the addition of a similar or identical component for the purpose of redundancy will move the nonredundant critical component to the list of redundant critical components. With each change of a nonredundant critical component to a redundant critical component through the addition of redundant components, the total vulnerable area of the aircraft will be reduced. With any component redundancy that is designed into the aircraft, the redundant components must be separated to preclude a single hit from killing both components.

In addition, further vulnerability assessment for multiple hits on the aircraft may indicate a requirement for more redundancy (i.e., four flight control computers). Not all nonredundant critical components will increase survivability through redundancy. If the damage of an nonessential component will cause the ultimate loss of another flight essential component, the damaged nonessential component is also a critical component. The damage modes of a component that could cause ultimate loss of the aircraft are explosion, fire, and loss of essential fluids. Examples of these damage modes are:

(1) liquid oxygen (LOX) bottles explosion

(2) ammunition drum explosion

(3) fuel tank fire/explosion or loss of fuel

(4) loss of essential hydraulic fluid

For the designer, the above discussion means that redundancy of any critical component that reduces the aircraft's vulnerable area is highly desirable. However, redundancy of critical components with adverse damage modes may increase A_V and decrease aircraft survivability. The damage mode and effects analysis (DMEA) of each component being studied must be conducted to determine the damage effect upon the vulnerable area.

C. COMPONENT LOCATION

Positioning of critical components during the aircraft design process has a direct impact upon the aircraft's vulnerability. From Ball [Ref. 1], component location design techniques include:

(1) positioning noncritical or tougher components to provide shielding for critical components

(2) effectively separating redundant components to ensure true single hit redundancy

(3) compactly grouping or overlapping critical components to reduce the aircraft vulnerable area or to present the least vulnerable aspect to a damage mechanism

4) locating or isolating components such that the possibility of cascading damage is reduced or eliminated

An example of improper positioning of a component is placing fuel tanks above, next to, or directly below any

hot surfaces such as engines or hot bleed air lines. If an enemy penetrator initiates a fuel leak onto the hot surface, fire damage or explosion may cause loss of the aircraft.

D. PASSIVE DAMAGE SUPPRESSION

Passive damage suppression is any vulnerability reduction feature that tends to contain or reduce the damage effects of a damage causing mechanism. Further, the passive term indicates that the survivability feature is built into or around the system, and initiates no responsive action following a hit by a damage mechanism. Passive damage suppression design techniques include damage tolerance, ballistic resistance, delayed failure, leakage suppression, fire and explosion suppression, and fail-safe response.

1. Damage Tolerance

Damage tolerance means that any aircraft component can continue to operate at an acceptable level after being damaged. This design technique also means that damage to a component will not propagate to other critical components. An example of a damage tolerant component is the aircraft's control surfaces. An elevator that is missing 25% of its surface area may not operate to peak efficiency, but with direct mechanical controls, the aircraft may still be controllable.

2. Ballistic Resistance

Ballistic resistance means that part or all of a damage mechanism is prevented from penetrating the

component. Most ballistic resistant materials are high strength and also very heavy in weight. The designer must consider the weight penalty and possible increase of susceptibility with the use of ballistic resistant materials. The designer may employ this technique by protecting a critical component with a ballistic resistant casing or by fabricating the component from a ballistic resistant material. An example of ballistic resistance is a flight control rod that is built to repel a high velocity fragment.

3. Delayed Failure

Delayed failure of a component will allow the aircraft to safely continue flight for a period of time after a damage mechanism has struck the aircraft. The desired length of time that a component will operate depends upon the function performed and the aircraft's mission. Time until failure of these components will range from allowing a safe return to base, to long enough to allow the crew to eject from the aircraft while if still in controlled flight. An example of delayed failure is an aircraft engine that will operate for a "long" period of time without lubrication.

4. Leakage Suppression

The prevention of leakage of any aircraft fluid is highly desirable. The retention of the fluid for use and also the prevention of the fluid from entering an area that could result in combustion are two benefits of self-sealing

design. Self-sealing construction has penalties of cost, weight, and increased size.

5. Fire and Explosion Suppression

Many projectiles are designed to cause combustion related damage after penetration. Antiaircraft artillery (AAA) projectiles may be either high-explosive (HE) or armor-piercing (AP). These projectiles may also contain an incendiary mixture (I) or a tracer material (T). HE-I antiaircraft projectiles are very common and are designed to produce secondary combustion damage to the aircraft. Any combustible material that can be ignited by the HE-I penetrator may cause a great deal of damage or even loss of the aircraft.

The suppression of fire and explosion can greatly decrease the vulnerable area and increase survivability due to the large amount of flammable material carried by tactical aircraft. Techniques to suppress fire and explosion are to prevent ignition, or to prevent the flame front propagation after ignition first occurs.

The design team must recognize any areas where combustion could occur. Fuel tank ullages and voids near fuel tanks or engines may provide the proper fuel air mixture for combustion. The removal of the combustible vapor by a forced inert gas system will not allow ignition to occur from any HE-I projectile or other source. Flexible foam in the fuel tanks will reduce the possibility of damage due to overpressure if ignition occurs. All of these survivability

enhancement features have design penalties. The penalties may include increased cost, weight, maintenance, and decreased fuel volume available.

6. Fail Safe Response

Any component that must be controlled over a wide range of conditions may become uncontrollable and revert to an unflyable operation if damaged in combat. Engine throttle control is a good example of the possible application of this technique. If the throttle to fuel control linkage becomes severed, fail-safe response will position the engine at a flyable power setting. Movable engine intake ramps are also critical to allow proper operation of the engine. If a ramp goes to a supersonic position while at low speed, a great deal of thrust is lost, possibly resulting in loss of the aircraft. Component designers must consider all possible damage to equipment that may be critical to flight.

E. ACTIVE DAMAGE SUPPRESSION

This design technique will actively reduce or contain the damage effects caused by a damage mechanism. The system incorporates a damage sensing ability with either an automatic response or a warning light to allow the pilot to take appropriate action. The most common example is a fire warning indicator with automatic or pilot operated fire extinguishers. Another example, is a fluid level sensor in the hydraulic reservoir that can detect a hydraulic leak and isolate the leak by an automatic isolation valve.

F. SHIELDING

The shielding of a component prevents the damage mechanism from reaching the component. Shielding may also be used to separate components and therefore isolate any damage. Because shielding must be very strong, the weight penalty may be significant. If shielding is necessary, the armor may be designed as a functional load carrying part of the aircraft. If armor plate is installed only in the shielding roll, it is parasitic; armor plate that is attached on the outside of an engine bay door is parasitic. However, if the engine bay door is constructed of a shielding material, the aircraft weight may be reduced. Shielding may also be used to separate two engines that are physically very close together. Damage to one engine can not cascade to the other engine because of the shielding between them.

G. COMPONENT ELIMINATION

The removal of a critical component from the design may decrease the aircraft's vulnerability if the function the component performed is no longer required, or another less vulnerable component can replace it. If complete elimination cannot be accomplished, any reduction of size will be beneficial. An example of component elimination is a fuel efficient aircraft that requires less fuel to accomplish its mission. Smaller fuel tanks mean less weight, reduced cost, and hence less vulnerable area.

Another example, is the replacement of LOX containers with a less vulnerable on-board oxygen generation system.

H. FINAL THOUGHTS

During conceptual design, most individual component designs are not considered. However, the size of each component, the location of the component, and system routing could affect conceptual design decisions. If this affect is not considered in the conceptual design, a latter change of the the design to reduce vulnerability may not be allowed, because of performance and/or fiscal constraints.

Designing an aircraft without concern for vulnerability reduction, because the aircraft's performance reduces it's susceptibility, may be very short sighted. Antiaircraft threats are increasing in capability with every new system introduced. Also, a 20 million dollar aircraft that is killed by a 200 dollar 7.62mm small arms weapon, is not justified. Performance and capability are required of modern combat aircraft, but because of their high cost, the purchase of high numbers of advanced aircraft may not be possible.

IV. SURVIVABILITY FROM THE REQUEST FOR PROPOSAL

A. THE REQUEST FOR PROPOSAL

The Department of Defense (DOD) has the very difficult task of predicting national defense threats. The DOD must study the threat and propose a system that can counter it. Because new aircraft systems may take ten to twelve years or more to design and begin construction, the sooner the defense industry and the DOD can select a design to develop, the quicker an aircraft can be put into service.

The RFP from DOD to the aircraft industry is the first draft of the specifications that may be required for the system. The specifications that are contained in the RFP are an attempt to meet the proposed threat that this vehicle will counter. The RFP specifications may be very specific, or they may prescribe the general outline of a new system and allow the defense industry to develop a detailed solution.

The aircraft conceptual design process is the systematic approach by the aircraft industry to satisfy the requirements of the RFP. The conceptual design phase is the idea level where aircraft shape, major component location, and sizes are studied. The conceptual design process will define the following:

(1) Concept that should be selected for more detailed design study.

(2) Technology of the aircraft that must be developed.

(3) Technology risk assessment of new systems.

(4) Impact of the required technology upon the concept.

(5) Economic constraints and risk assessment.

Table IV-1 lists possible RFP specifications that DOD may send to the aircraft industry. Some of these requirements may be specific, and others may indicate the general desires of the DOD. The example of size/weight limitations may come from aircraft carrier restrictions. Many of the specifications deal with aircraft capabilities. These capability specifications may directly affect the aircraft's susceptibility (e.g., the specifications on signatures and performance), and the "survivability" specifications may mainly address the aircraft's vulnerability.

B. SURVIVABILITY CONSIDERATIONS

The requirements of the RFP are guidelines that are used to begin the conceptual design process. The requirements that are given will be used to estimate the aircraft's weight/size, aerodynamics, and propulsion parameters. These parameters are then packaged together to give design concepts that will be candidates for further design study.

As in many engineering disciplines, some design objectives may conflict with other, also important, parameters. This is especially true when considering survivability enhancement features. An example of

TABLE IV-1

POSSIBLE RFP REQUIREMENTS

A. CONFIGURATION

1. Size Limitations
2. Gross Weight Limitations
3. Signature Considerations
4. Crew

B. PERFORMANCE

1. Mission Profile
2. Weapons Payload
3. Max Speed
4. Ceiling
5. Approach Speed
6. Takeoff Distance
7. Landing Distance
8. Load Factors
9. Turning Performance
10. Acceleration

C. SPECIAL CONSIDERATIONS

1. Life Cycle
2. Maintenance
3. Reliability
4. Avionics and Countermeasures Equipment
5. Survivability

increasing the maximum speed of a design will mean larger engines and also larger fuel tanks to fly the higher speed. The increased speed may decrease susceptibility, but the larger engines and fuel tanks will probably increase vulnerability. This conflict of parameters has led to survivability being a consideration after the design has been completed. Mott and Freitag [Ref. 4:pp 46-47] discuss the problems and deficiencies of current aircraft design practice. The discussion focuses on the problem that aircraft survivability has not been a part of the conceptual design process. This problem is most recognized when retrofit or follow-on design survivability enhancements cause performance compromises and/or significant cost increases that would not have been required if done during conceptual design.

The conceptual design process today is heavily computerized. The automation of the design process permits the quick analysis and evaluation of the concepts under study. Simplified engineering computations that often rely on historical data are the basis for the computer automation. The historical data provides the data base for initial sizing, optimization, and trade off studies. The incorporation of survivability enhancements in the computer computations may not exist at this point because the aircraft of the past have not been specifically designed for survivability. New technology impact, incorporation of

survivability enhancement, and unusual aircraft configurations have to be adjusted for, because previous aircraft statistics cannot account for these new design factors.

1. Susceptibility of the Design

The ability of the aircraft to avoid being hit by an enemy damage mechanism depends upon many factors. Many RFP specifications will directly influence the susceptibility of a design. Many specifications will affect several design parameters, and as mentioned previously, some desired specifications may compromise other design goals. A brief presentation is given below of the impact of some of the design specifications can have upon "survivability."

a. Size

In general, the smaller the aircraft, the harder the aircraft is to hit. Smaller size may also contribute to reduced signatures.

b. Weight

The weight depends somewhat upon size, however, many light weight materials such as composites may replace heavier aircraft materials without loss of strength. Reduced weight will affect many performance parameters as well as allowing smaller engines (same thrust/weight), smaller wings (same wing loading), and increased weapon/fuel payload.

c. Signature

The reduction of all aircraft signatures can decrease susceptibility. During conceptual design of a strike fighter aircraft, the radar and visual signatures will be most affected by aircraft materials, paint, geometry, and size. IR signature reduction is mostly a function of the engines and nozzles.

d. Mission Profile

The profile should utilize the best cruise altitude and mach number until detection becomes possible. From the possible detection point, minimum exposure time to hostile action while maintaining a minimum detection profile is desired.

e. Weapons Payload

Because the payload is such a sensitive design parameter, the minimum acceptable weapons payload should be considered. Increased accuracy of weapons (e.g., precision guided) will allow reduced payloads at the same mission attainment measure. Longe range launch and leave weapons will allow the aircraft greater flexibility in the target area, and greater offensive range. Reduced payloads will also allow smaller aircraft size or increased fuel load and range.

f. Maximum Speed

The less time the aircraft is exposed to enemy action, the less susceptible the aircraft will be during a

ground attack. High speed may also increase tracking errors. Speed for the fighter role, will increase available maneuverability and intercept capability. Enemy missile threat envelopes may decrease in size due to increase speed.

g. Turning Performance

Higher turning performance may give the aircraft an advantage in the air to air role. For the air to ground mission, high turn rates used in jinking may reduce firing accuracies of antiaircraft weapons.

2. <u>Vulnerability of the Design</u>

The last RFP requirement of Table IV-1 is survivability. The survivability of the aircraft after being hit depends upon it's vulnerability. The survivability requirement of the RFP normally addresses vulnerability reduction as earlier specifications relate to susceptibility. The ability of the aircraft to withstand a hit by an enemy projectile is influenced by many factors. The reduction of vulnerable area of the design will decrease vulnerability and thus increase aircraft survivability.

Figure 4-1 is from Briggs [Ref.5], and shows combat aircraft losses by functional area. This data, derived from the South East Asian conflict, indicate that the fuel system was the highest cause of aircraft loss. This agrees with the fact that the fuel system normally presents the

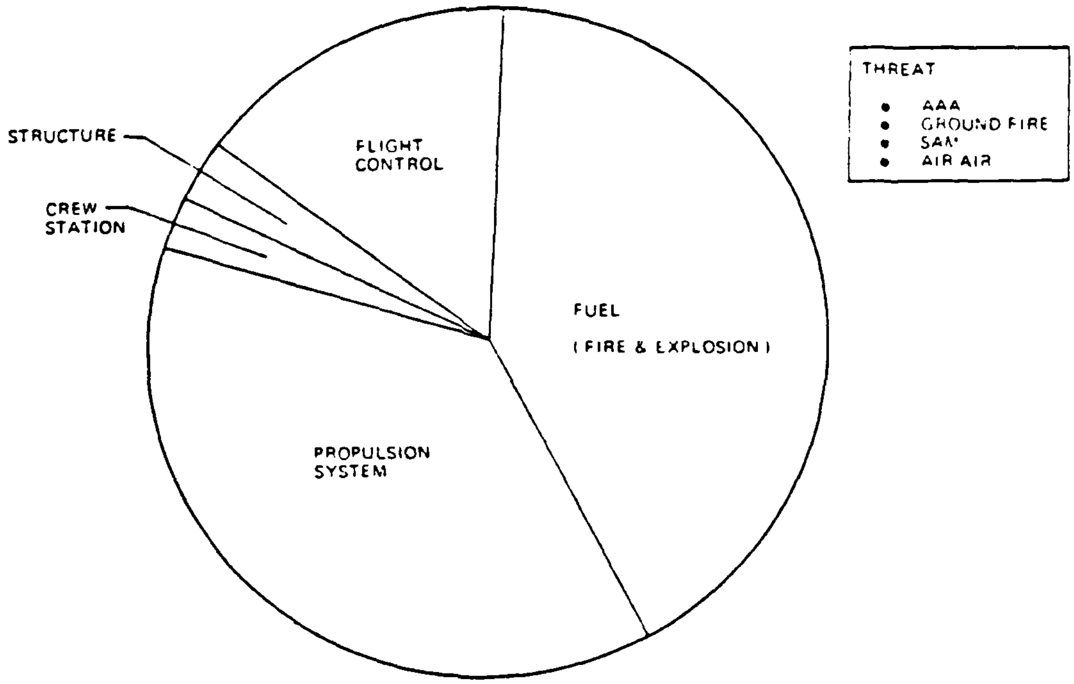


Figure 4-1 Aircraft Losses by Functional Area

largest area to enemy damage mechanisms and has the largest $P_{k/h}$.

The six vulnerability reduction concepts will be considered in each of the following aircraft functional areas, that have historically been the most vulnerable.

(1) structures

(2) crew station

(3) propulsion system

(4) fuel system

(5) flight control system

Where the designer must compromise between vulnerability reduction and susceptibility reduction, a study of the end results must be made to determine the best selection of susceptibility and vulnerability reduction concepts.

a. Structures

The structure of the aircraft includes all load bearing and aerodynamic shaping structures. The design of the primary structures should be redundant to allow for full loading after damage has occurred. The entire structure should also be as damage tolerant as possible to reduce design vulnerability. The materials used in the construction of the aircraft will greatly effect the vulnerability of the structure. Desired material properties are increased strength, and reduced weight, cost, and corrosion.

b. Crew Station

Although the crew station presents a small area to the enemy, it must be a part of the vulnerability reduction effort during the design level. Space around the cockpit is limited, so proper placement of noncritical components may provide some protection for the crew. Shielding of the aircrew and critical components in the cockpit, may be required to protect the crew station from threat projectiles. Parasitic shielding with armor should be avoided, as extra weight and bulk may be a penalty.

c. Propulsion System

The propulsion system includes the engine, intake, exhaust duct, lubrication system, accessories, and engine power controls. All of this equipment must be in good operating condition for the propulsion system to produce designed thrust for the aircraft. Because these subsystems are critical to the production of thrust, the vulnerable area of the propulsion system may be high. Complete loss of engine thrust may come from foreign object ingestion, inlet flow distortion, and fuel ingestion. All six vulnerability reduction concepts may be used to increase the survivability of the propulsion system.

Redundancy with separation, will prevent aircraft kill from a single hit. Separation of multiple propulsion subsystems is required due to adverse damage effects that may cascade from one component to another, and to preclude a single hit kill.

Proper location of the propulsion system components, may prevent aircraft kill. Propulsion system hot surfaces should not be near any type of flammable substance in order to prevent fire or explosion. Engine intakes and fuel tank interfaces should be avoided to prevent fuel ingestion, foreign object ingestion, or inlet flow distortion.

Passive damage suppression can be applied in many ways to reduce the probability of propulsion system kill. The engine may be less complex and have less moving parts, resulting in the ability to construct the engine with greater damage tolerance. Ballistic resistant construction of critical components in the propulsion system may be considered. Lubrication systems may be constructed of self-sealing materials. Engine throttle controls may be designed to fail to a flyable power setting if the system is severed.

Active damage suppression may include a fire detection and extinguisher system in each engine bay with multiple shot capability. Engine performance instruments in the cockpit may allow early shutdown of a damaged engine and prevent secondary damage effects. Automatic engine shutdown may be considered in multiple engine aircraft, however the ability to override the automatic shutdown should be available to the pilot if the situation calls for drastic measures.

(2) forced inert gas in fuel tank ullages and voids

(3) fuel tank foam to reduce explosion overpressure

(4) material in dry bays, voids and ullages to prevent explosive mixtures

(5) antimisting fuels

Hydraulic ram is a damage process of a compartment that contains a fluid. When a penetrator enters a liquid compartment, energy from the projectile is transferred by pressure waves through the fluid. The tank may suffer severe rupture due to the high pressures on the walls of the container. The hydraulic ram damage may affect other components if the tank walls are adjacent to other critical components. Hydraulic ram damage may be reduced by;

(1) minimum fuel tank, engine and engine intake interface

(2) dual walled tanks where adjacent components are critical

(3) smooth fuel tank contours to prevent high pressures

(4) tear resistant tank materials

(5) large volume tanks may absorb greater pressures

e. Flight Control System

The flight control system includes all control surfaces, control linkages, flight control computers, and the hydraulic systems to power the control surfaces. Disruption of control signal, loss of control power, loss of motion sensors, damage of a control surface, and hydraulic fluid fires may lead to an aircraft kill. The

Component elimination can directly reduce the vulnerable area of the propulsion system. Furthermore, the reduced number of components may reduce the size and weight of the engine.

Shielding critical components that are still vulnerable to damage mechanisms should be considered after other vulnerability reduction concepts have been applied. Parasitic shielding should be avoided, as extra weight will be a penalty. Shielding may also act as the firewall to contain areas of possible fire and explosion.

d. Fuel System

The fuel system may represent the largest contributor to the aircraft vulnerable area. Vulnerability reduction can greatly reduce the $P_{k/h}$ and thus the vulnerable area of the fuel system. The fuel system includes the fuel tanks, transfer lines, pumps, and valves. Fuel depletion, fire/explosion, or hydraulic ram may lead to aircraft kill. Fuel depletion may be prevented by;

(1) self-sealing tanks and lines

(2) redundant tanks and lines

(3) ability to cross feed tanks and engines

(4) capability to gravity feed engines

(5) transfer lines inside fuel tanks to reduce vulnerable area

Fuel fire and explosion suppression techniques may include;

(1) fire detection and extinguishers

control system was the third largest contributor to aircraft vulnerability during the South East Asian conflict.

Direct mechanical control systems are changing to analog or digital fly by wire control systems. Advances in flight control technology with high speed computers allow the designer to relax the static stability of the aircraft to increase the aircraft's performance. Component vulnerable area of these complex control systems may be reduced by applying the six vulnerability reduction concepts.

Redundancy of the entire control system may prevent a single hit kill. Greater redundancy of vulnerable systems may be considered to reduce probability of kill to multiple hits. Control surfaces may also be designed to be redundant. Independent vertical tails, leading and trailing edge devices, speed brakes, and horizontal tails may provide adequate control if one control surface is completely ineffective. For fly by wire control systems, the flight control computer must be able to sense the loss of a control surface and apply the remaining control surfaces to the aircraft control laws. This system may be referred to as a self healing flight control system.

Component location may prevent the loss of several components due to one hit. For example, redundant control cables or wire bundles should not be collocated.

They should be routed to take advantage of other components as protection, and also separated by enough distance to ensure true single hit redundancy.

Fail-safe response shall be designed for all control surfaces. Given any control component failure, no control surface shall be given a hard over command. This may allow time for corrective action or at least time for a controlled ejection.

Active damage suppression may be applied to reduce the $P_{k/h}$ of the control system. The ability to switch from a fly by wire to a jam free mechanical system is an active response to a failure.

Shielding of flight control components is a possible way to reduce the vulnerability. However, proper redundancy with separation may be a better use of the extra weight. If shielding is still to be used, it should protect as many critical components as possible without compromising redundancy with the lack of separation.

Component elimination can reduce vulnerable area by reducing the physical size of the control system. The smaller system will also be harder to hit. High technology flight computers are being built smaller and smaller which reduces vulnerable area. Hydraulic actuators that only contain fluid for themselves will reduce the vulnerable area by elimination of the lines and reservoirs.

C. LONG RANGE STRIKE FIGHTER RFP

A long range strike fighter will be examined here as an example of the survivability enhancement features previously discussed. The aircraft as designed, must be able to perform its mission, and survive in the hostile environment.

A multirole strike fighter may be a compromise of performance goals, but because of the high cost of combat aircraft and limited space on aircraft carriers, multimission aircraft must be considered. Air superiority over the battle field and also the ability of self protection must be included. The example guidelines for the aircraft are given below.

1. Configuration

The Strike Fighter must be capable of operation from aircraft carriers. All size and weight limitations associated with carrier operation shall be met. Both size and weight shall be as small as possible while still satisfying all specifications.

All aircraft signatures shall be as small as possible. The visual signature shall be reduced by small size prior to applying other visual reduction techniques. The radar cross section shall be reduced to delay detection. Internal weapons, fuel, and electronics shall be considered to reduce the RCS. RAM and active interference shall be considered following all efforts to reflect the

radar signal away from the radar receiver. The infrared signature shall be reduced to minimize aircraft susceptibility to IR detection and missiles. A two dimensional nozzle shall be considered to reduce the IR radiation of the exhaust plume. Aural signature shall be as small as possible, however there shall be no compromise of performance capability.

The strike fighter crew size shall be as small as possible without sacrificing aircraft capability. Crew size shall be no more than two.

2. Performance

The Strike Fighter mission profile is shown in Figure 4-2. Maximum range altitude and mach number is flown until maximum enemy radar range. From that point, speed shall increase to minimize the reaction time available to the enemy. At the range of predicted radar detection, low altitude ingress shall be flown utilizing the terrain to reduce detection possibility. Speed in the target area shall be at least mach 1.2. Supersonic weapons delivery is desired.

Weapons payload of the strike fighter are four 1000 lb medium range Skipper weapons, two Sidewinder air to air missiles, and one 20mm gun with 300 rounds. The internal bomb bay shall also be able to carry and launch two Harpoon anti-ship missiles in place of the Skipper weapons.

Other strike fighter performance specifications are listed below:

(1)	max speed at altitude:	mach 1.8
(2)	max speed at sea level:	mach 1.2
(3)	max ceiling:	50,000 ft.
(4)	approach speed:	135 kts
(5)	take off distance:	3000 ft.
(6)	landing distance:	3500 ft.
(7)	max load factor:	n = 9
(8)	sustained turn(M=.9, 15K)	16 deg/sec
(9)	instantaneous turn(.9, 15K)	22 deg/sec
(10)	acceleration(.9 to 1.4, 30K)	50 sec max

3. Special Considerations

The special considerations of the strike fighter RFP directly affect conceptual design. The life cycle of the aircraft will have an impact upon the size and weight of all load bearing structures. Maintenance and reliability may affect the decisions on the location of each aircraft component. Easy access to components that require frequent maintenance is desired. Avionics and countermeasures requirements of the RFP may go into great detail to specify the capability required. The designer must reserve space in the aircraft design for all equipment, and also provide the required environment. Location of the avionics and countermeasures equipment should be considered. Strike Fighter avionics and countermeasures equipment shall be

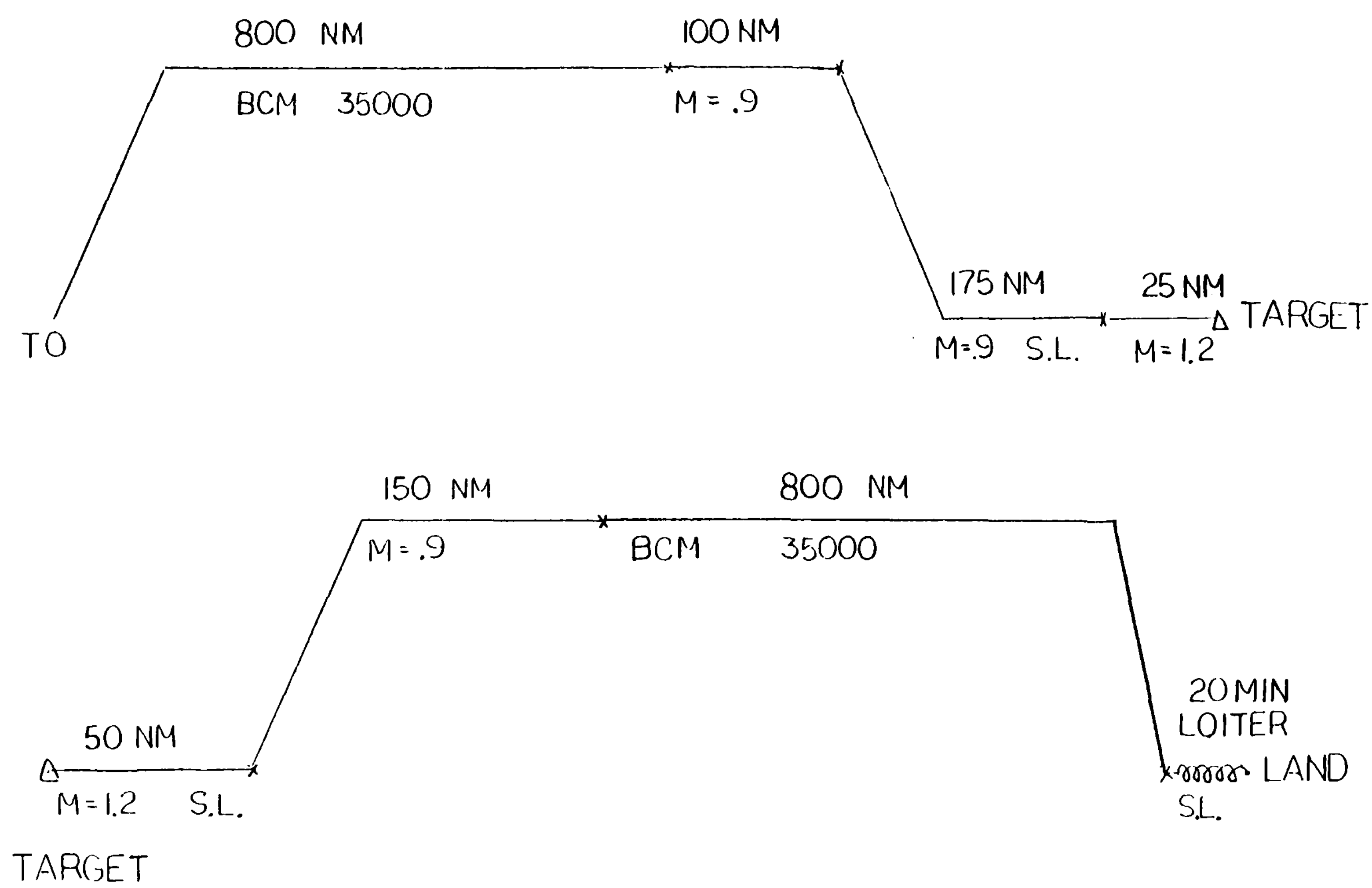


Figure 4-2 Strike Fighter Mission Profile

located to reduce aircraft RCS, and drag. Location of the electronic equipment shall not compromise their own performance.

Survivability specifications of the RFP set the vulnerability posture of the design. Specific guidance for vulnerability reduction may be given, however the Strike Fighter RFP presented here will give general guidance and allow the aircraft industry to package the design. Vulnerable area considering a single enemy hit shall be as "small" as practicable. Strike fighter survivability, performance, and capability goals shall be equal in importance.

D. NEW AIRCRAFT TECHNOLOGY

Using technology that is readily available may be referred to as off-the-shelf technology. There may be many reasons to use off-the-shelf technology including low risk, cost, maintenance, and high reliability. However, to significantly increase the survivability, performance, and capabilities of combat aircraft, new technology must be developed. Examples of emerging technology that may offer high payoffs for military aircraft are:

(1) signature reduction

(2) supersonic cruise

(3) active flutter suppression

(4) self healing flight control systems

(5) relaxed static margin

(6) thrust vectoring

(7) terrain flight management

(8) rough field capability

(9) advanced composites

(10) safe high speed crew escape

(11) advanced engines

(12) conformal carriage

(13) advanced airfoils

(14) variable camber

(15) surfaced launched air targeted air to air weapons

(16) advanced air to surface weapons

V. STRIKE FIGHTER CONCEPTUAL DESIGN

The RFP has stated that performance, capability, and survivability should all be equal goals during the conceptual design. Many design parameter compromises will have to be studied as goals conflict in some areas. Utilization of new technology may aide the designer in overcoming some conflicts.

A. GEOMETRY

The strike fighter initial layout is shown in Figures 5-1 and 5-2. For the canard wing configuration, the wing aerodynamic center is behind the aircraft center of gravity, and thus the wing is stabilizing. Therefore, the canards function only for control and thus require less area. Volume coefficients of canards are 1/4 to 1/2 of conventional horizontal tails. The canards are located immediately aft of the cockpit to preclude any visual interference, and also aide in smooth changes of aircraft cross sectional area.

The internal bomb bay is large enough to carry and launch the specified payload of four Skippers or two Harpoon missiles. Sidewinders are located on each wing tip, and blended into the wing as much as possible. The 20 mm gun is located in the port wing root, and is completely submerged. A thin radar reflective membrane covers the gun

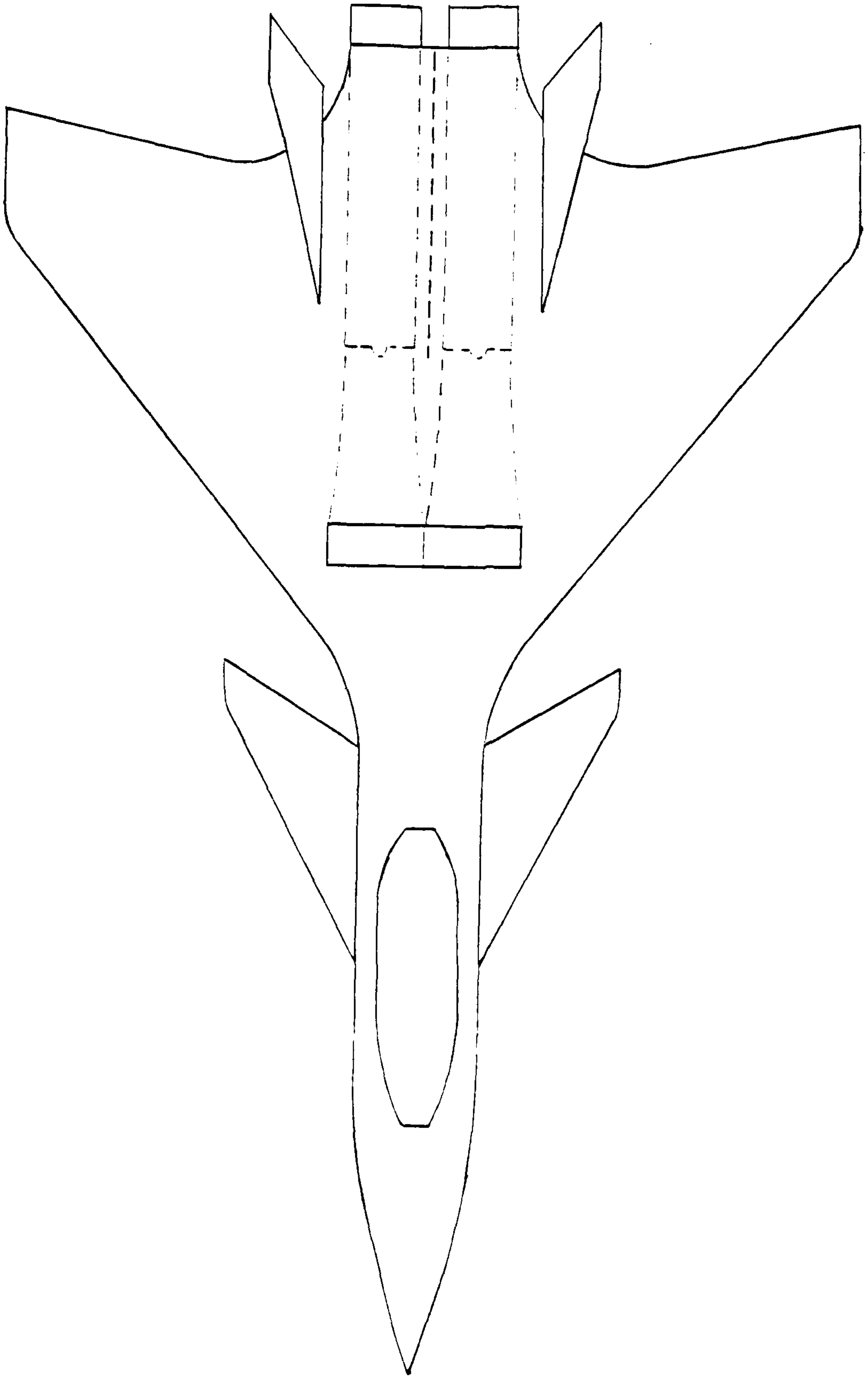


Figure 5-1   Strike Fighter Layout

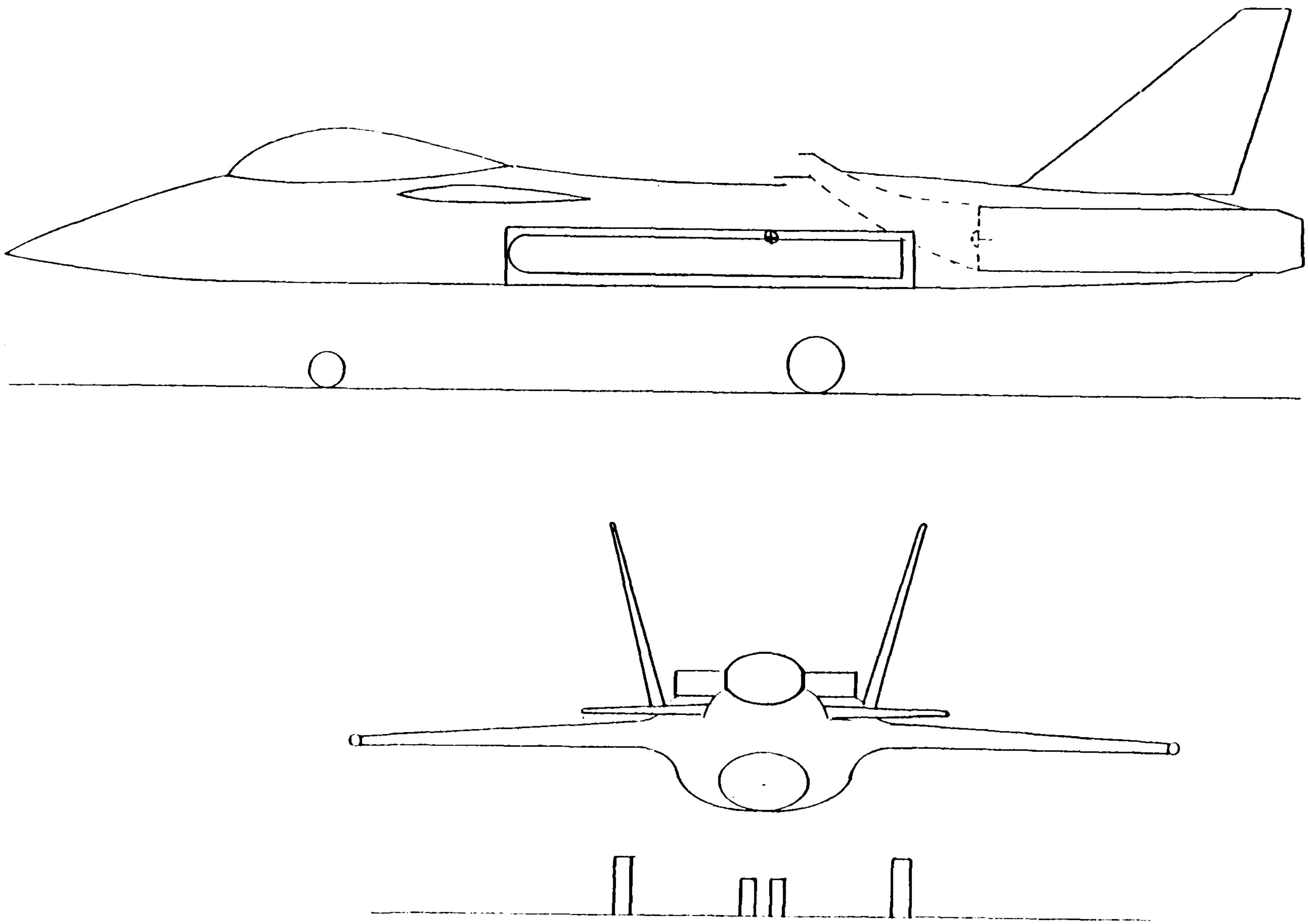
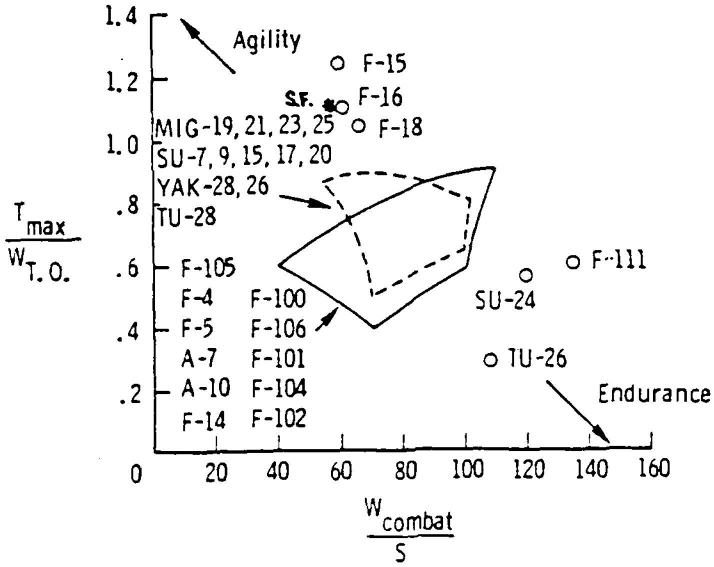


Figure 5-2 Strike Fighter Layout

cavity to reduce its contribution to the RCS. The membrane will be destroyed after the first round out of the gun.

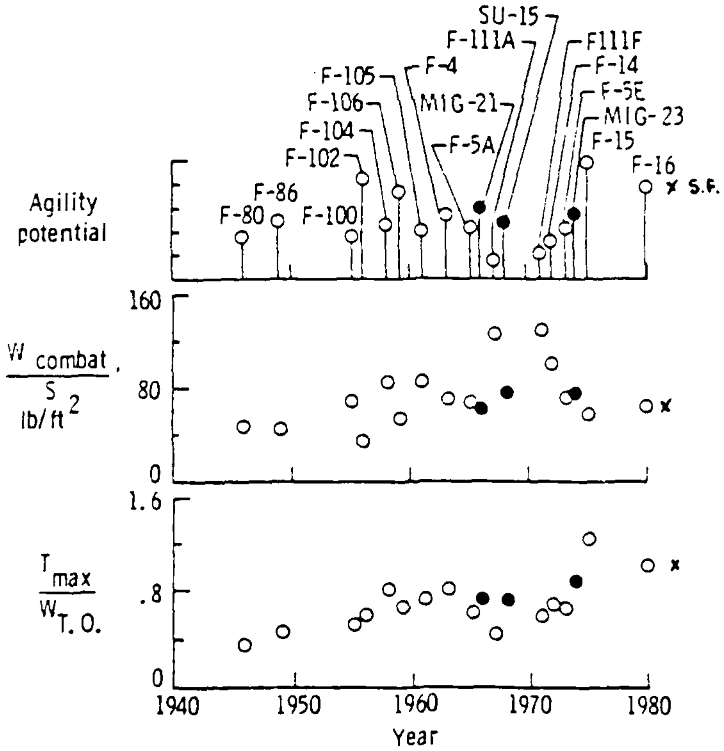
Top mounted engine intakes may aide in reducing the aircraft's RCS from depressed angles. The edges and interior of the intakes will be made of a radar absorbant material. Top mounted intakes will also reduce probability of foreign object damage due to loose objects on the ground. Auxiliary intake doors are included in the design to aide engine performance at high angle of attack. These doors will normally be closed, and will open automatically as the aircraft increases angle of attack.

Aircraft wing loading (W/S) is a design parameter that has conflicting results. Low wing loading will generally increase turning performance particularly at low speed, while high wing loading will aide in fuel efficient cruise flight. Turning performance is affected by the coefficient of lift (C_L) and aircraft thrust to weight (T/W) ratio. High aspect ratio (AR) wings will be more efficient at subsonic speeds, while a low AR will reduce drag at transonic and supersonic speeds. Low AR is also much simpler to construct resulting in lower structural weight. Figures 5-3a and b are from Spearman [Ref. 6], and show fighter aircraft wing loading and thrust to weight trends. Figure 5-3b illustrates aircraft agility potential, which is the T/W divided by W/S. This shows that the higher W/S for cruise efficiency will decrease agility, but an



Thrust-to-weight versus combat wing loading for U.S. and U.S.S.R. aircraft.

Figure 5-3a



Agility potential for U.S. and U.S.S.R. aircraft.

Figure 5-3b

increase of T/W will recover the lost agility. The Strike Fighter T(max)/W(t.o.) is 1.1 and the W(combat)/S is 60.6. The Strike Fighter is included in Figures 5-3a and b for comparison.

TABLE V-1

BASELINE STRIKE FIGHTER

Engines	2
Crew	1
Design Mach	1.5
Thrust/Weight	1.1
Est. Gross Wt.	34,000 lbs
Payload	5,000 lbs
Fuel	11,500 lbs
Empty Weight	17,500 lbs
Wing Geometry	
AR	2.5
Area = S	400 sq. ft
Span = b	31.6 ft
W/S (Take Off)	85.0 lb/sq. ft
W/S (Combat)	60.6 lb/sq. ft
L.E. Sweep	51.0
Root Cord	20.3 ft
Tip Cord	5.1 ft
Taper Ratio	0.25
Thickness Ratio	5%

Canard Geometry (Exposed)

Area = S	43.9 sq. ft
AR	2.0
Volume coeff.	0.101
L.E. Sweep	63.0
Root Cord	8.13 ft
Tip Cord	1.25 ft
Taper Ratio	0.15
Mean t/c	4%

Vertical Tail Geometry (Total Exposed)

Area = S	74.7 sq. ft
AR	2.7
Volume Coeff.	0.0635
L.E. Sweep	51.0
Root Cord	8.13 ft
Tip Cord	2.50 ft
Taper Ratio	0.31
Mean t/c	4%
Tail Angle	15.0

Fuselage Geometry

Length	50.0 ft
Max Height	5.8 ft
Max Width	9.4 ft
Inlet Capture Area	3.7 sq. ft

B. STRUCTURE

The structure is designed to be damage tolerant to enemy damage mechanisms. Major structural components are redundant to prevent a single hit kill. The aircraft is designed with a wing that may utilize a straight through wing box. This will allow a lighter wing box that is also easier to construct. Ring frames may also be used near the engine to support the wing.

The fuselage is designed with smooth changes of shape to reduce and redirect its contribution to the RCS. Continuous load paths in the fuselage will reduce structural weight. The blended wing body is designed to reduce supersonic drag and thus reduce fuel consumption. Secondary benefits from the blended wing body are:

(1) thicker wing root for fuel or landing gear

(2) reduced subsonic C_{d0}

(3) improved span efficiency

(4) increased drag divergence Mach number

The use of construction materials other than conventional aluminum will aide the designer in reducing the aircraft's weight and corrosion problems.

Organic composites are increasingly being used to reduce aircraft weight. The F-18's structure is approximately 20% composite by weight. With 20% composites, the aircraft's structural weight is reduced by approximately 10% below that of conventional aluminum. Maximum use of

composites may only increase to 60% because many aircraft structural components such as landing gear, engines, and engine mounts can not be constructed from composites. An aircraft constructed from 60% composites would reduce the structural weight by approximately 16%. This information is presented by Powers, Driggers, and King [Ref. 7]. All high weight payoff structures of the Strike Fighter are constructed of composites. This reduces the estimated structural weight by 10%.

C. CREW STATION

Because the Strike Fighter is a single pilot design, ballistic protection of the cockpit will be provided. The floor and lower sides of the cockpit are a two-plate composite armor that can defeat 23mm HEI projectiles. Two of the aircraft's four flight control computers are also protected by the same armor. From Remers [Ref. 8], it is estimated that the armor system weighs eight lbs/sq. ft.

The life support system includes an on board oxygen generation system (OBOGS) combined with an on board inert gas generation system (OBIGGS). This system eliminates the need for vulnerable LOX converters.

D. PROPULSION SYSTEM

The Strike Fighter is a two engine design, and all propulsion subsystems are redundant. The engines are separated by a vertical shield to prevent cascading damage.

Two multiple shot fire extinguisher systems are located between the engine intakes. The engines are a "rubber" variation of the F 404 engine with afterburner. Specifications for the "rubber" engine are listed below.

(1)	Nominal Thrust	18,700 lbf
(2)	Static Airflow	163 lbm/sec
(3)	Engine Weight	1,990 lb
(4)	Engine Length	152 inches
(5)	Max Diameter	33 inches
(6)	Compressor Face Dia.	29 inches
(7)	Pressure Ratio	25:1
(8)	Two-D. Nozzle Length	30 inches

The top mounted intakes are designed to minimize the aircraft's RCS from monostatic radars on the ground. The intakes are a two shock design which will provide 90% pressure recovery up to Mach 2.0. The auxiliary air intakes are designed to minimize thrust loss at high angles of attack during subsonic flight.

Two dimensional exhaust nozzles are designed for thrust vectoring, IR and RCS signature reduction. Independent exhaust nozzle vectoring may increase turning performance and aircraft control redundancy. Vectoring may also reduce take off and landing distance. The extension of the exhaust system due to the nozzle addition may decrease propulsion system vulnerability from small IR guided missiles guiding on the hot tail pipe.

E. FUEL SYSTEM

The fuel requirement of the Strike Fighter is 11,500 lbs or 1,692 gallons of JP-5. Fuel Tanks in the wings require 270 cubic inches/gallon of jet fuel. If foam is used in the wing tanks to suppress fires and explosion in the ullage, 3% fuel retention and 2% fuel displacement will cause an increase to 284 cubic inches/gallon required. Fuel tanks in the fuselage require 251 cubic inches/gallon. The Strike Fighter wings contain 5,000 lbs of fuel and the fuselage contains 6,500 lbs of fuel. The fuselage tanks are located in the aircraft so that there is no fuel tank and engine inlet interface. The fuselage tanks are also located away from any aircraft hot material, such as engines, to prevent a fire due to leaking fuel. The fuselage tanks are inerted by the on board inert gas generation system (OBIGGS) to reduce tank vulnerability to fires and explosions. Six separate fuel tanks (four in the wings and two in the fuselage) provide redundancy and reduce the possibility of kill due to fuel depletion. Each engine feeds from a separate fuselage sump that can gravity feed the engine if required. Both fuselage tanks are constructed of self sealing materials over the lower half to preserve get home fuel. Figures 5-4 and 5-5 indicate the fuel tank locations.

Extra fuel tanks may be placed in the bomb bay in place of the Harpoon missiles. This will add 3,000 lbs of fuel

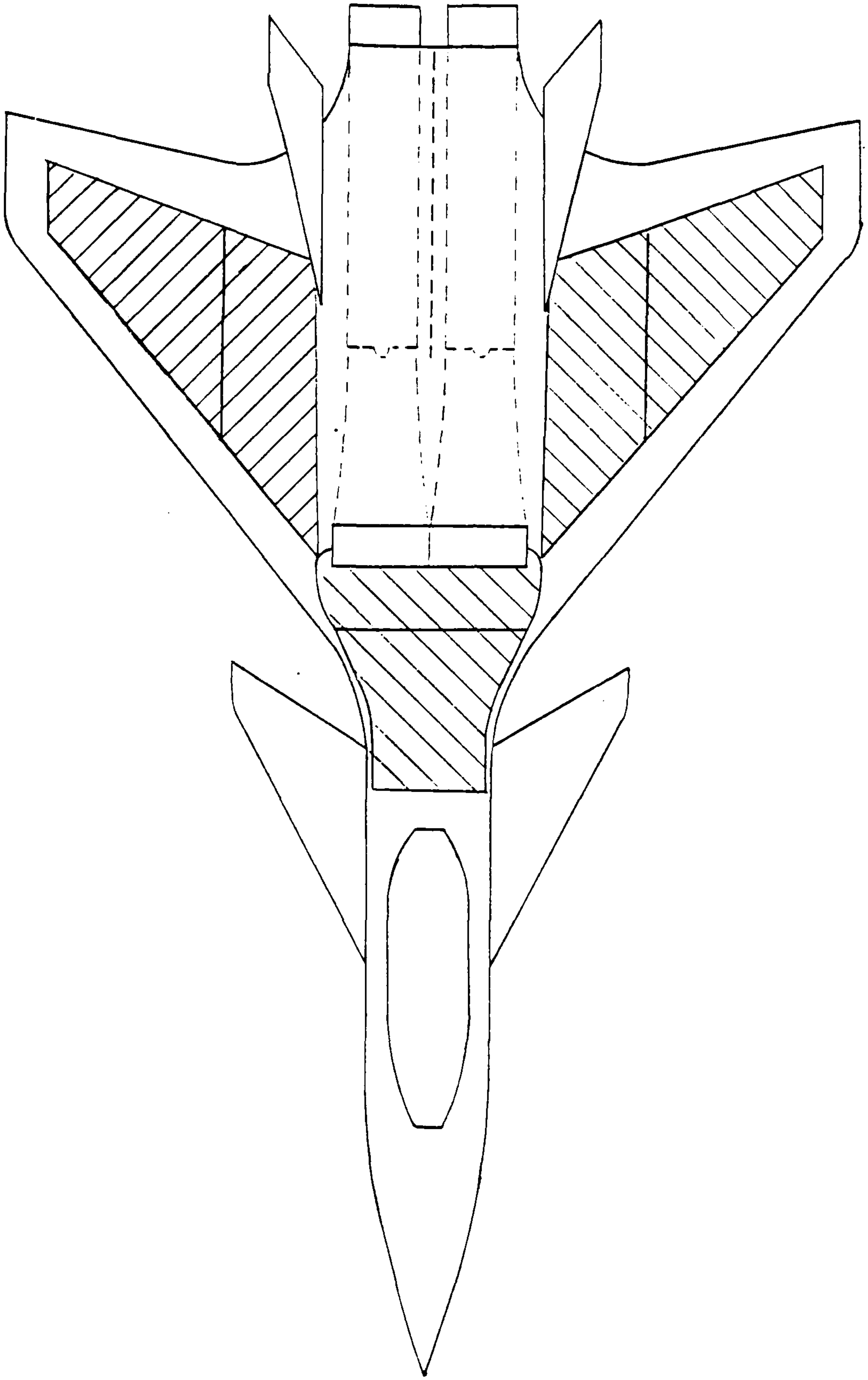


Figure 5-4   Strike Fighter Fuel Tank Locations

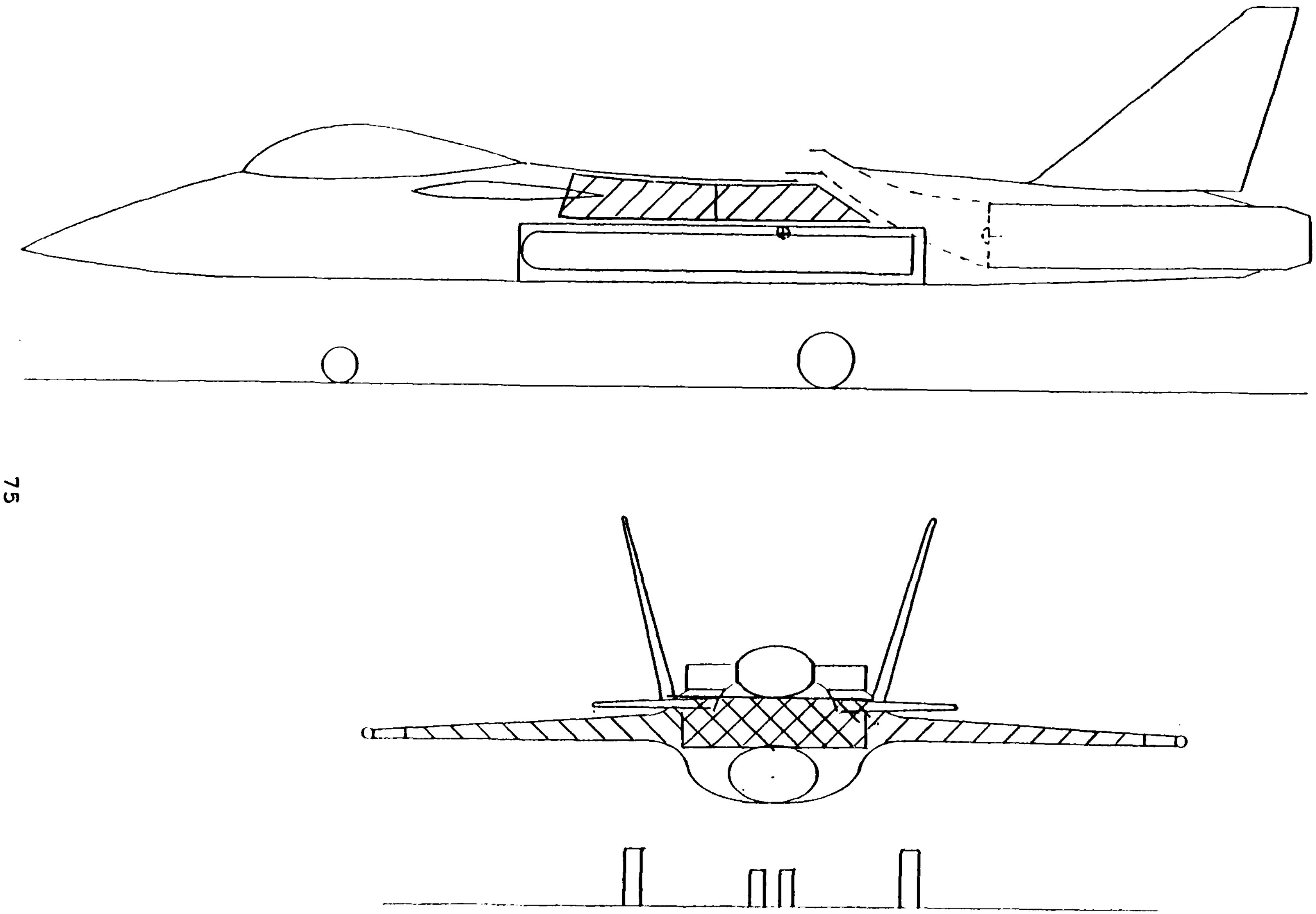


Figure 5-5   Strike Fighter Fuel Tank Locations

for ferry missions. Total fuel load for ferry is 14,500 lbs.

F. FLIGHT CONTROL SYSTEM

A quadruplex fly by wire flight control system will independently manage the following control devices.

(1) Leading and Trailing Edge High Lift Devices

(2) Independent Canards

(3) Rudders on Each Vertical Stabilizer

(4) Vectoring Nozzles

Artificial intelligence will be used in the flight control system to manage the various devices to account for damage to one or more of the the devices, i.e., self healing. Routing of control wire bundles are separated in the Strike Fighter to prevent any single hit kills.

Flight control hydraulic systems have been replaced by actuators that contain hydraulic fluid only for themselves. Electric actuators that do not require any fluid are also a possibility for the Strike Fighter. All actuators are redundant and designed to be jam resistant.

G. AVIONICS AND COUNTERMEASURES

The Strike Fighter avionics and countermeasures equipment are all internal to the aircraft. Electronic countermeasures (ECM) equipment that is matched to the aircraft must have sufficient volume reserved during conceptual design. Aircraft signatures will have a direct impact upon the proper ECM equipment selected. ECM

equipment location may be critical to effective operation and must also be considered during conceptual design. Some aircraft equipment is extendable when required for use including the forward looking infrared receiver (FLIR) and laser target designator. Extending this equipment will increase the aircraft's RCS. Expendables may be launched from both the top and bottom of the aircraft fuselage depending upon aircraft altitude. An all weather radar is integrated into the low altitude attack navigation system. A standard avionics and weapons bus allows for quick change of electronic equipment to meet specific requirements. Increased electronic warfare equipment may be mounted in place of the weapons in the bomb bay.

H. WEAPONS

All weapons of the Strike Fighter, except the Sidewinders, are internal. The aircraft is sized to carry either Skipper or Harpoon. Folding fins on the internal weapons allow for compact carriage in the bomb bay. Sidewinder fins are also folded during carriage to reduce their contribution to the aircraft's RCS. The high accuracy of these weapons allow a minimum weapons load to obtain a high MAM. The reduced payload will allow survivability enhancement without severe aircraft performance penalties. The extended delivery range of these weapons may allow the aircraft to never enter the enemy's antiaircraft weapons envelopes, which will increase aircraft survivability and the MOMS.

VI. COMBAT EFFECTIVENESS

A. GENERAL

Effectiveness ranking of combat aircraft is very difficult. Aircraft have different capabilities for each mission they perform. Some "popular" capabilities concerning aircraft effectiveness are maximum speed, payload, range, turn rate, target detection range, weapon accuracy, and weapon launch range. Note the absence of survivability in these "popular" measures. However, any valid study of combat aircraft effectiveness must include survivability in the evaluation.

Multi-mission aircraft such as the Strike Fighter pay penalties to be able to perform more than one mission. Performance penalties from vulnerability and/or susceptibility reduction should normally be avoided, however a decline in aircraft performance may be justified if there is an increase in effectiveness of the aircraft.

B. MAXIMUM SPEED

Increasing the speed of early combat aircraft was important as faster aircraft were often better in combat. Maximum speeds of WWI aircraft averaged approximately 120 kts. Faster aircraft could always attack slower aircraft and also safely disengage when the situation dictated. An aircraft that was 25 kts faster than the average had a

significant advantage. The 145 kt aircraft was 21% faster than the average.

WWII propeller driven aircraft maximum speeds were approximately 360 kts. The introduction of the gas turbine powered Me 262 launched a new era in aircraft and maximum speed. The maximum speed of the Me 262 was 470 kts at 20,000 ft. Although the Me 262 had some design problems, its performance advantage was recognized by all. [Ref. 9]

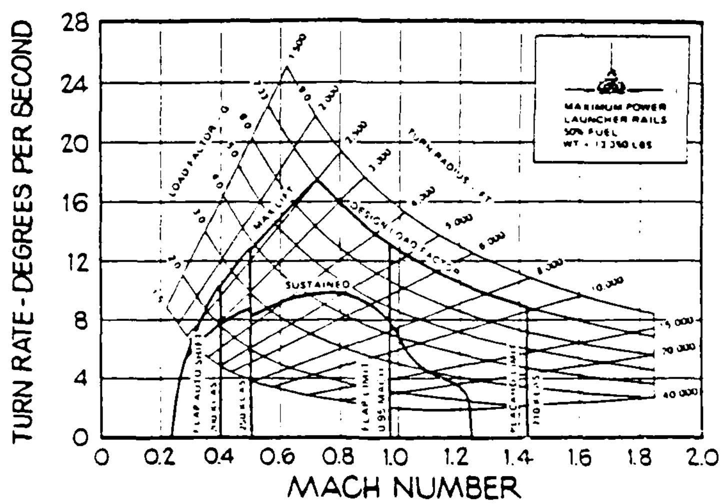
The maximum speed of the aircraft of the Korean conflict was near Mach 0.9. Best cruise speed for these aircraft was from Mach 0.8 to 0.9. Because the maximum speed and cruise speed were close, they flew near their maximum speed all of the time. Afterburners for extra thrust and speed were developed soon after the jet engine, but operational Korean conflict fighters did not have them.

Intuitively, more speed for a combat aircraft would make a better aircraft. Vietnam conflict aircraft had maximum speeds in the Mach 2.2 area. More than 100,000 sorties of Mach 2.2 capable aircraft were flown during the Vietnam conflict. [Ref.10] However, as Figure 6-1a shows, the capability of high Mach was not used in the combat arena. Figure 6-1b shows the reason that high Mach numbers are not used in combat. The maximum turn rates and minimum turn radius for today's aircraft (major parameters for close in combat) takes place in the Mach 0.7 range. Cornering speed, the speed of maximum turn rate, is a

VIETNAM COMBAT SPEEDS

- NOT ONE SECOND OF FLIGHT COMBAT TIME AT MACH 2.2 SPEED (OR ABOVE) WAS RECORDED.
- NOT ONE SECOND OF FLIGHT COMBAT TIME AT MACH 2.0 SPEED (OR ABOVE) WAS RECORDED.
- NOT ONE SECOND OF FLIGHT COMBAT TIME AT MACH 1.8 SPEED (OR ABOVE) WAS RECORDED.
- ALMOST NO TIME AT 1.6 MACH (OR ABOVE) WAS RECORDED (SECONDS).
- EXTREMELY LITTLE FLIGHT TIME AT 1.4 MACH (OR ABOVE) WAS RECORDED (MINUTES).
- REMARKABLY LITTLE TIME AT 1.2 MACH (OR ABOVE) WAS FLOWN (HOURS).

F-5E TURN PERFORMANCE-15,000 FEET



Figures 6-1a & 6-1b

function of maximum lift and maximum load factors. While the capability of high Mach may be used to intercept and/or disengage the enemy, cornering speeds are where air to air combat will take place. The high thrust to weight ratio that allowed Mach 2.2 was actually used by the pilot to increase turning performance.

The Strike Fighter performing an air to ground attack may use speed differently than during the fighter mission. The aircraft attempts to fly as low and as fast as possible to hide from radar and other detection systems. Maximum speed may reduce the exposure time to enemy weapons. However, strike aircraft normally operate at low altitudes to take advantage of terrain masking, and flying both extremely fast at low altitude may be difficult to safely accomplish. Furthermore, the properties of the atmosphere make high speed flight at low altitude very fuel costly. Maximum speed is a function of dynamic pressure (q).

$$q = .5 * \text{density} * V^2$$

Figure 6-2 shows a constant dynamic pressure of 1700 PSF. At sea level, 1700 PSF equates to Mach 1.07 or 708 kts TAS, where as 1700 PSF at 40,000 ft equates to Mach 2.50 which is equal to 1,434 kts TAS.

Figure 6-3 shows a corridor for a low level strike. Flight speeds above Mach 1.0 may have a buffet problem due

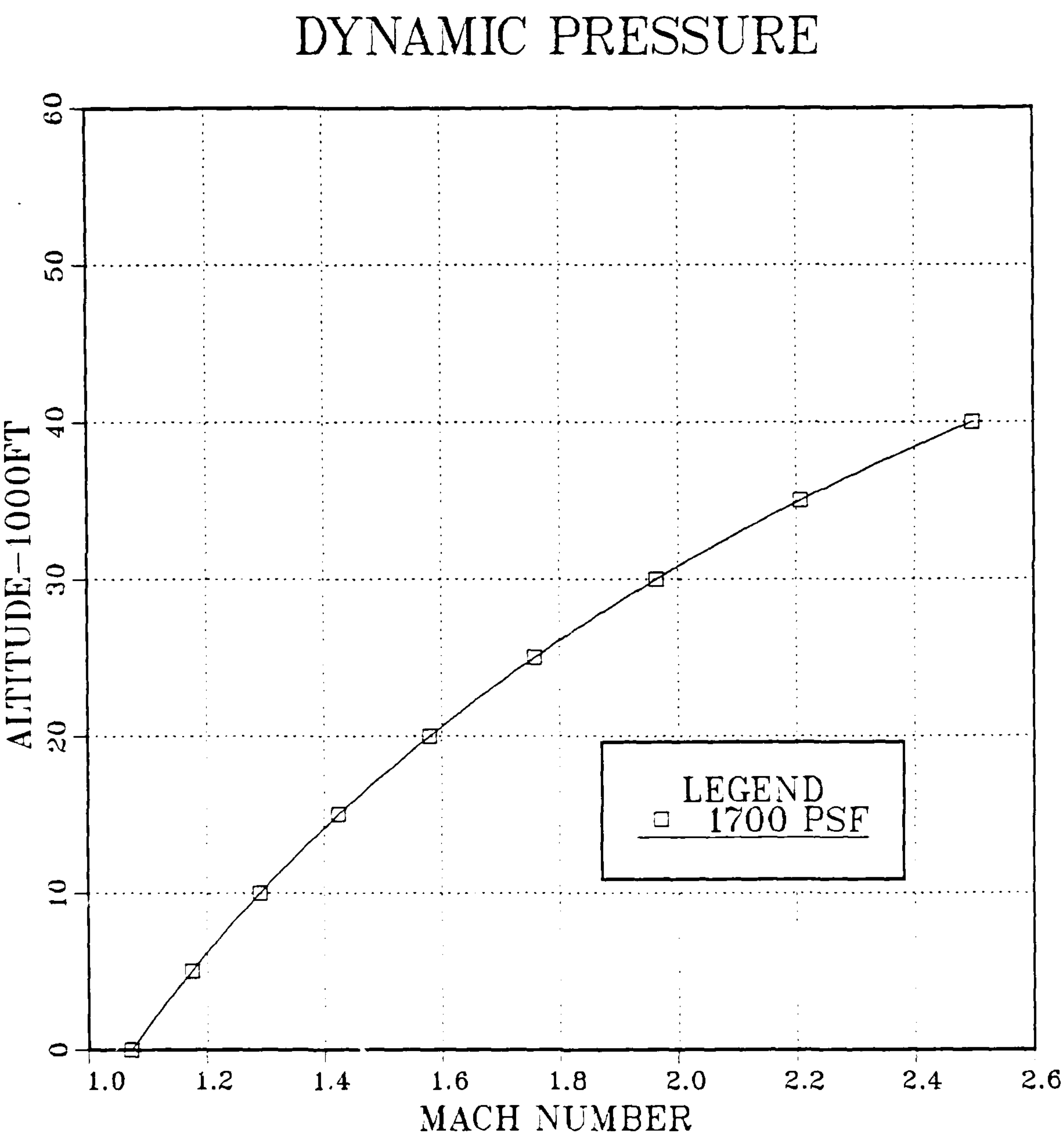
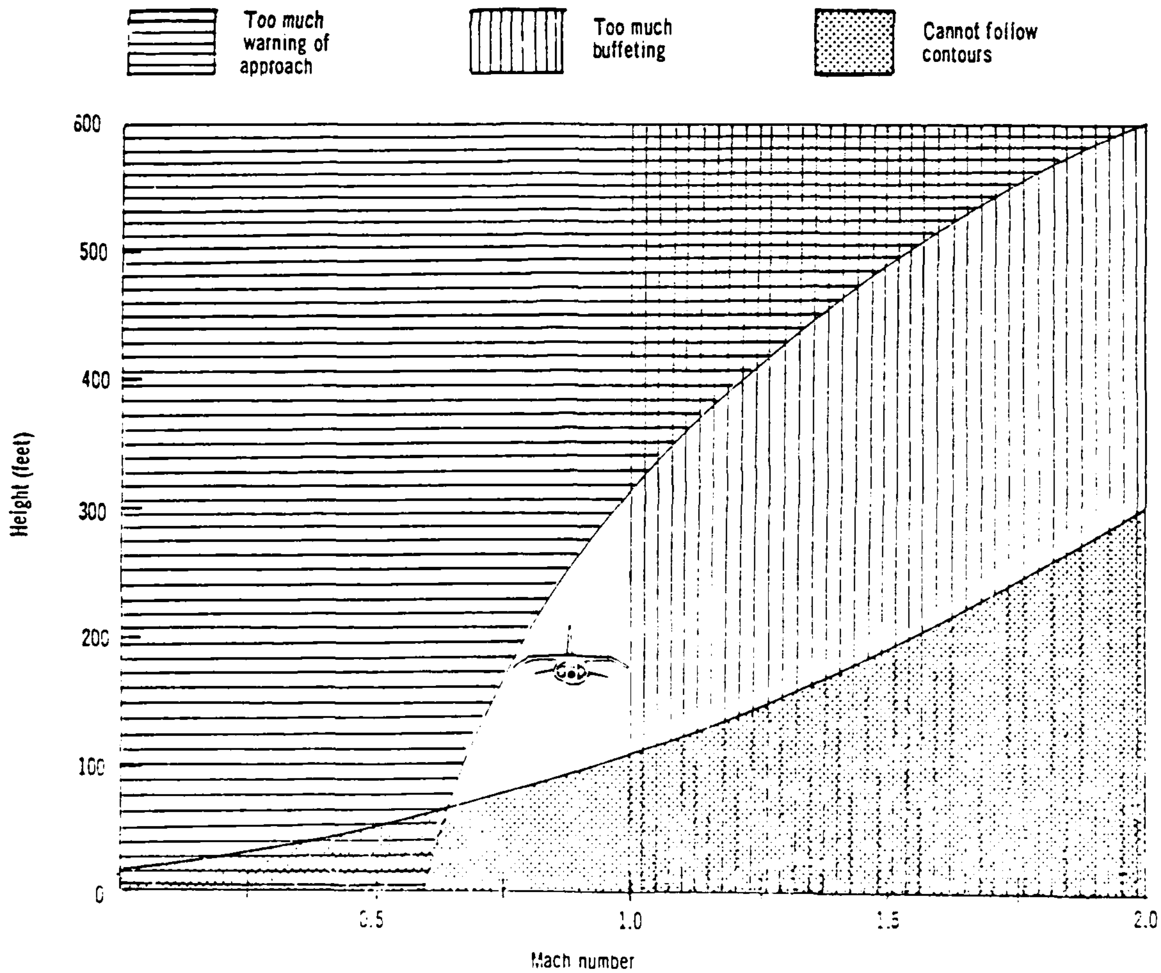


Figure 6-2 Dynamic Pressure



Simplified corridor along which an aircraft might make a low level strike

[Ref. 11]

Figure 6-3 Low Level Strike Corridor

to compressibility, especially if the aircraft must be fuel efficient at subsonic speeds. Buffet at low altitude is very fatiguing on the crew however, it can be safely maintained for short periods of time. This effect may be reduced by use of digital fly-by-wire control systems. However, at too high a ground speed, the aircraft can not follow the terrain without excessive acceleration on the aircraft.

Another approach is to fly very high and very fast with a small RCS to delay detection and reduce enemy reaction time. Precision guided weapons would be used to maintain a high MAM.

C. PAYLOAD RANGE

Aircraft payload range is another very important performance parameter. Payload range is the product of weapons payload and range in nautical miles. Aircraft mission profile must be constant when comparing different aircraft. For aircraft carriers, high payload range means that the carrier may launch attack aircraft further away from hostile territory. High payload range for fighters also allows intercept further from the carrier (outside hostile weapons launch range).

Figure 6-4 shows the flexibility that high payload range will give an aircraft. For short range missions, the aircraft may reduce fuel load and increase weapons payload. For long range missions, weapons payload will be reduced

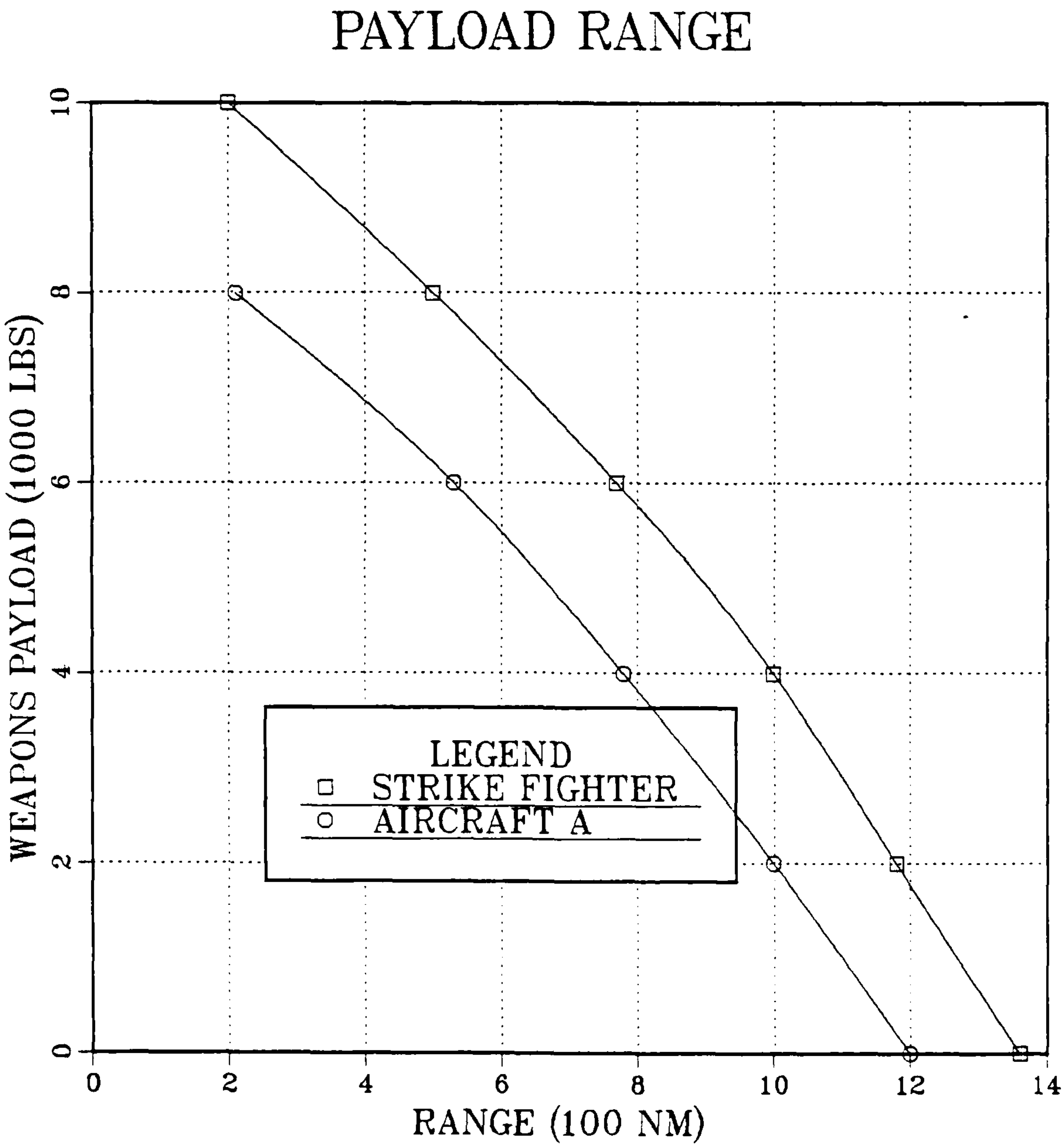


Figure 6-4 Payload Range

for increased fuel. Drag is not a factor for the Strike Fighter when considering weapons loads up to 4000 lbs. Weapons loads over 4000 lbs have to be externally carried, which will increase drag and aircraft RCS. Aircraft A of Figure 6-4 is similar in size to the Strike Fighter, however all weapons and extra fuel are mounted externally. Aircraft A's advantage may be short range fighter missions where the external fuel tanks and weapons racks may be dropped off the aircraft.

D. WEAPONS EFFECTIVENESS

Also important to combat effectiveness is the effectiveness of the weapons that the aircraft will employ. High technology weapons which are higher in lethality will allow a lower payload for a specified MAM. However, high technology weapons may be ineffective when higher technology countermeasures are used. For example, low technology weapons, such as the gun, must be considered for the fighter, the "dumb" iron bomb capability must be considered for the attack aircraft.

The product of explosive payload and aircraft range for a specific aircraft profile may give a relative estimate of effectiveness. However, weapons type and delivery range also affects the aircraft capability. A weapons adjustment factor may aide in evaluation of the aircraft design. Possible adjustments for air to ground weapons are:

(1) Mk 80 series 0.7

(2) Cluster Weapons 0.9

(3) Short Range Guided 1.1

(4) Long Range Self Guided 2.2

Air to air weapons adjustment factors may be:

(1) Gun 0.7

(2) Short Range Radar Guided 1.1

(3) Short Range IR Guided 1.4

(4) Medium Range Radar Guided 1.6

(5) Long Range Self Guided 2.2

The payload range of the Strike Fighter is shown with different air to ground weapons and is based upon these adjustment factors.

(1) Two Harpoon 2,200,000 nm-lb explosive

(2) Four Skipper 2,200,000 nm-lb explosive

(3) Four Mk 83 1,400,000 nm-lb explosive

E. MEASURE OF MISSION SUCCESS

The MOMS which is discussed in chapter two, uses both probability of aircraft survival and the mission attainment measure to evaluate the aircraft effectiveness. Figure 2-3 shows the maximum MOMS is approximately 0.72 for the SAM encounter. Because the MOMS is relatively flat near the maximum value of 0.72, a slight reduction of the MOMS which will slightly decrease the MAM and increase the P_s may mean a great deal to force levels over an extended conflict. Figure 1-1 shows that a small variation in the loss rate over a 30 day conflict may significantly change the force remaining.

Strike Fighter MOMS are dependent upon mission and weapons carried. The design decisions in this study were made by evaluating the MOMS using the Skipper against a SAM site, and extensive vulnerability reduction design concepts are incorporated into the Strike Fighter to increase P_s. With the MAM increased by precision guided weapons, the MOMS is increased. Long range weapons delivery will also increase the MOMS by increasing P_s. A weapons payload that is destructive and also keeps the aircraft outside enemy threat envelopes is effective. These high technology weapons allow a lighter payload and can maintain a high MAM without increasing the aircraft's susceptibility.

F. VULNERABILITY AND SUSCEPTIBILITY ASSESSMENT

The effectiveness study of combat aircraft must include vulnerability, susceptibility, and survivability assessment. Because no aircraft can have zero susceptibility, vulnerability reduction may be critical to the aircraft's survival. The Strike Fighter is designed to have a "small" vulnerable area. Many of the design decisions that reduced the vulnerable area had no adverse effect upon aircraft performance because this reduction was accomplished in the conceptual design stage.

Vulnerability and susceptibility reduction may cause a penalty in increased weight and cost. The benefits of armor at the cost of decreased performance may be difficult to judge, but a pilot would certainly accept a 1% loss of

thrust for a 75% decrease of IR signature. A trade off study early in the design of the aircraft will indicate if the reduction features are worth the increase in financial cost. These survivability enhancement features may never be cost effective if the aircraft is never used in combat, but if the kill of one 30 million dollar aircraft is avoided, the entire program cost may be recovered.

Several computer programs can be used to assess survivability of the conceptual design aircraft. These computer programs require various levels of input data to provide aircraft probability of survival in a given scenario. Some of the inputs may be:

(1) Hostile Defensive Weapons

(2) Characteristics of the Hostile Weapons

(3) Aircraft Mission Profile

(4) Vulnerability of the Aircraft against each Hostile Weapon

(5) Countermeasures

(6) Evasive Action

(7) Aircraft Signatures

Some of these programs are: [Ref.4]

(1) TACOS II

(2) SIMFIND2

(3) TAC AVENGER

(4) EVADE II

(5) P001

(6) DATAM 1

(7) COVART

(8) SCAN

(9) MECA

(10) SAMS

(11) MICE

(12) VISAP

The above assessment programs must start with a design so the the software can analyze it. However, the designer wants information from the survival analyst to determine appropriate design selection. Automated computer design may allow survivability assessment of various designs in a very short time. Trade-off studies of the output may aide in design decisions. Other factors that also affect design decisions are aircraft reliability, maintainability, repairability, and life cycle costs. Trade-offs must take all of the desired aircraft qualities into account. A balance of trade-off studies must be used prior to establishing the design. The aircraft's performance, capability, survivability, and maintainability must all be considered while at the same time satisfying cost constraints. The most effective aircraft possible must always be the goal of the design team.

VII. SUMMARY AND RECOMMENDATIONS

A. EFFECTS OF CONCEPTUAL DESIGN DECISIONS

The conceptual design of a combat aircraft is a very complex process. The interaction of hundreds of design parameters affect the design aircraft. The goals of the aircraft are also complex and there often must be some compromise. Some of the design goals may include:

(1) Small Signatures

(2) Large Payload

(3) Long Range

(4) High Speed

(5) Fuel Efficient

(6) Survivable

(7) Inexpensive

(8) Reliable

(9) Easily Maintained

The solution to some compromises may come through emerging technology. Technology such as:

(1) Variable Sweep Wings

(2) Advanced Composites

(3) Advanced Engines

(4) Variable Camber

(5) Digital Fly-By-Wire

(6) Artificial Intelligence

(7) Long Range Weapons

(8) Susceptibility Reduction

(9) Vulnerability Reduction

The proper application of the above aircraft technology must be considered during the conceptual design to obtain the maximum results. Retrofit of aircraft may not increase aircraft combat effectiveness up to that possible in conceptual design.

B. SUSCEPTIBILITY REDUCTION

Many of the conceptual design decisions will affect the probability of hit, or aircraft susceptibility. Reduced susceptibility and increased aircraft performance seem to relate to each other, but susceptibility reduction is much more than just increased aircraft performance. The six susceptibility reduction concepts are repeated below.

(1) Signature Reduction

(2) Tactics

(3) Noise Jammers and Deceivers

(4) Threat Warning

(5) Threat Suppression

(6) Expendables

Because of the survivability goals of Table I-1, and the interaction of the concepts, the above list of susceptibility reduction concepts has been reordered. The survivability goals one through three which are:

(1) Delay detection as long as possible

(2) If detected, avoid being fired at

(3) If fired at, avoid being hit

The order may give a more effective aircraft if the conceptual design team works from the top down to satisfy the survivability goals. Table VII-1 lists susceptibility reduction design guidance.

Susceptibility and vulnerability reduction along with aircraft capability, reliability, and maintainability will result in the aircraft's combat effectiveness. All of the "ilities" must be considered to obtain the most effective aircraft possible.

C. VULNERABILITY REDUCTION

Reduction of the probability of aircraft kill given a hit on the aircraft is accomplished by application of the six vulnerability reduction concepts repeated below.

(1) Component Redundancy with Separation

(2) Component Location

(3) Passive Damage Suppression

(4) Active Damage Suppression

(5) Component Shielding

(6) Component Elimination

These vulnerability reduction concepts may aide the designer in accomplishing goals four through six of Table I-1 which are:

(4) If hit, avoid weapon system kill

(5) If hit, avoid aircraft kill

(6) If hit and not killed, can be easily repaired

Table VII-2 lists possible aircraft kill modes and design guidance to reduce the probability of kill given a hit.

TABLE VII-1

SUSCEPTIBILITY REDUCTION DESIGN GUIDANCE

SIGNATURE REDUCTION		
RCS Reduction	(a)	Reflect signal away from receiver
	(b)	Absorption (RAM)/(RAS)
	(c)	Impedance loading
Visual signature reduction	(a)	Minimize aircraft size
	(b)	Smokeless engines
	(c)	Paint
	(d)	No canopy glint
IR signature reduction	(a)	Mask hot parts
	(b)	Cool exhaust plume
	(c)	Decrease exhaust plume size
TACTICS	(a)	High maximum speed
	(b)	Good agility
	(c)	Good handling qualities
	(d)	Good range
	(e)	Fuel efficient
	(f)	Effective weapons
	(g)	Minimize pilot workload
NOISE JAMMERS AND DECEIVERS	(a)	Make provisions for internal electronic jammers and associated equipment
THREAT WARNING	(a)	Make provisions for internal threat warning devices
THREAT SUPPRESSION	(a)	Self protection missiles and/or guns
	(b)	Anti-radiation missiles
EXPENDABLES	(a)	Make provisions for internal chaff, flares, jammers, aerosols, etc.

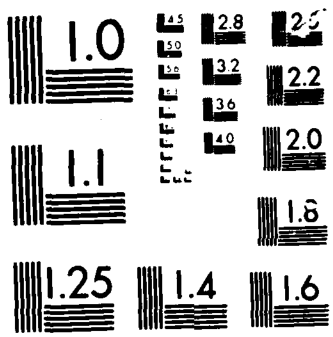
TABLE VII-2

VULNERABILITY REDUCTION DESIGN GUIDANCE

FUEL SYSTEM		
Supply Depletion	(a)	Minimize leakage
	(b)	Good fuel efficiency
	(c)	Redundant fuel tanks
	(d)	Redundant fuel feed
Fire and Explosion	(a)	No fuel tank/line and hot surface interface
	(b)	Ullage inerting or foam
	(c)	Void space inerting or foam
	(d)	Space fillers
	(e)	Extinguishing systems
	(f)	Antimisting fuel
Hydraulic Ram	(a)	smooth fuel tank contours
	(b)	damage tolerant fuel tanks
PROPULSION SYSTEM		
Fuel and Foreign object ingestion	(a)	Redundant engines
	(b)	No fuel tank and engine intake interface
	(c)	Hydraulic ram tolerant engine intakes
Intake distortion	(a)	Hydraulic ram tolerant engine intakes
	(b)	Fail-Safe intake ramps
Lubrication starvation	(a)	Redundant systems
	(b)	Self-Sealing lines and tanks
	(c)	Ballistic resistant
	(d)	Location/Shielding

AD-A168 555 SURVIVABILITY CONSIDERATIONS DURING AIRCRAFT CONCEPTUAL DESIGN(U) NAVAL POSTGRADUATE SCHOOL MONTEREY CA R J GILMAN MAR 86 2/2

UNCLASSIFIED F/G 1/3 NL


1.0
2.8
2.2
3.2
3.6
2.0
4.0
1.1
1.8
1.25
1.4
1.6

FLIGHT CONTROL SYSTEM

Control Path Continuity	(a)	Redundancy
	(b)	Location/Shielding
	(c)	Reduction in size
	(d)	Ballistic/temperature tolerant linkages
	(e)	Jam free design
Reduction of control power loss and effects	(a)	Leak suppression
	(b)	Ballistic resistant actuators
	(c)	Location of actuators
	(d)	Rip-Stop actuators
	(e)	Fail-safe position
Control surface and hinges	(a)	Reconfigurable control surfaces
	(b)	Damage tolerant
	(c)	Redundant load paths
	(d)	Fail-safe position
Hydraulic Fires	(a)	Leak suppression
	(b)	Location
	(c)	Less flammable fluid
CREW STATION	(a)	Redundancy
	(b)	Shielding
	(c)	Location
STRUCTURAL	(a)	Redundancy
	(b)	Damage tolerant construction
	(c)	Fail-safe (multiple load paths and crack stoppers)
	(d)	Location (prevent secondary damage)

D. RECOMMENDATIONS

Combat aircraft of tomorrow must be able to perform many missions. The complexity and cost of modern combat aircraft will not permit a large quantity to be produced. Production rates of new aircraft can not be rapidly increased during a crisis because of the supply of critical material. Furthermore, survivability modifications may not be possible after the start of hostilities due to the length of the conflict and the time necessary for modifications. Survivability enhancement must be applied to our aircraft during the conceptual design process.

Combat aircraft conceptual design has not included survivability enhancement in the past, because survivability features were not included in previous aircraft. The strict historical basis for conceptual design can be made more flexible with computer aided design as a tool. Furthermore, allowances for survivability enhancement and unconventional design can fit into the computer aided conceptual design process. Application of susceptibility and vulnerability reduction concepts during conceptual design may financially cost very little, while significantly increasing combat effectiveness.

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